What can we learn from neutrinos?

David McKeen
University of Washington
Fermilab Theory Seminar, March 24, 2016

We have learned a lot about already

1930: proposed by Pauli to explain beta decay spectra

1934: Fermi model

1956-2001: 3 flavors detected

1957: Pontecorvo proposes oscillations to explain “hint” (that went away) of neutrinos emitted in beta decay

1998: Oscillations conclusively observed

We have learned a lot about already

1930: proposed by Pauli to explain beta decay spectra

1934: Fermi model

1956-2001: 3 flavors detected

1957: Pontecorvo proposes oscillations to explain “hint” (that went away) of neutrinos emitted in beta decay

1998: Oscillations conclusively observed

1973: Volkov & Akulov discover SUSY trying to explain lightness of neutrinos!

Neutrino oscillations require neutrino masses

Eigenstates of H

$$|\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle \qquad\qquad |\nu_e(t)\rangle = \cos\theta e^{iE_1 t}|\nu_1\rangle + \sin\theta e^{iE_2 t}|\nu_2\rangle$$
$$|\nu_\mu\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle \quad \Rightarrow \quad |\nu_\mu(t)\rangle = -\sin\theta e^{iE_1 t}|\nu_1\rangle + \cos\theta e^{iE_2 t}|\nu_2\rangle$$

$$P_{e\to\mu} = |\langle\nu_\mu|\nu_e(t)\rangle|^2 = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

(Assuming the relativistic limit $t \simeq L, E_i \simeq p + \dfrac{m_i^2}{2p}$)

$$P_{e\to\mu} \neq 0 \Rightarrow \Delta m \neq 0$$

Mixing angle controls amplitude, mass diff. controls osc. length

$$L_{\text{osc}} \sim \text{meter}\left(\frac{\text{eV}^2}{\Delta m^2}\right)\left(\frac{E}{\text{MeV}}\right)$$

Neutrino masses require new physics

In SM, neutrinos appear as part of SU(2) doublet with Y=1/2

$$L_i = \begin{pmatrix} \nu_i \\ \ell_i \end{pmatrix}$$

Symmetric combination is SU(2) triplet (with Y=1 so has neutral component) and can provide mass after EWSB

$$L_i L_j$$

No candidates in SM!

Weinberg tells us to couple this to $\dfrac{H^2}{\Lambda} \to \dfrac{v^2}{\Lambda}$

Current status

Well fit by 3 flavor oscillation!

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass splittings $\Delta m^2_{12} = \Delta m^2_{\odot} \simeq 7.5 \times 10^{-5}\ \mathrm{eV}^2, \ |\Delta m^2_{13}| = \Delta m^2_{\mathrm{atm}} \simeq 2.5 \times 10^{-3}\ \mathrm{eV}^2$

$|U_{e2}|^2, |U_{\mu 2}|^2 + |U_{\tau 2}|^2$ solar neutrinos

$|U_{e1}|^2 |U_{e2}|^2$ KamLAND

$|U_{\mu 3}|^2 \left(1 - |U_{\mu 3}|^2\right)$ atmospheric/accelerator

$|U_{e3}|^2 \left(1 - |U_{e3}|^2\right)$ short baseline reactors

$|U_{e3}|^2 |U_{\mu 3}|^2$ long baseline accelerator

$$\tan^2\theta_{12} = \frac{|U_{e2}|^2}{|U_{e1}|^2} \sim 32^\circ$$

$$\tan^2\theta_{23} = \frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2} \sim 45^\circ$$

$$\sin\theta_{13} = |U_{e3}| \sim 8^\circ$$

Plan

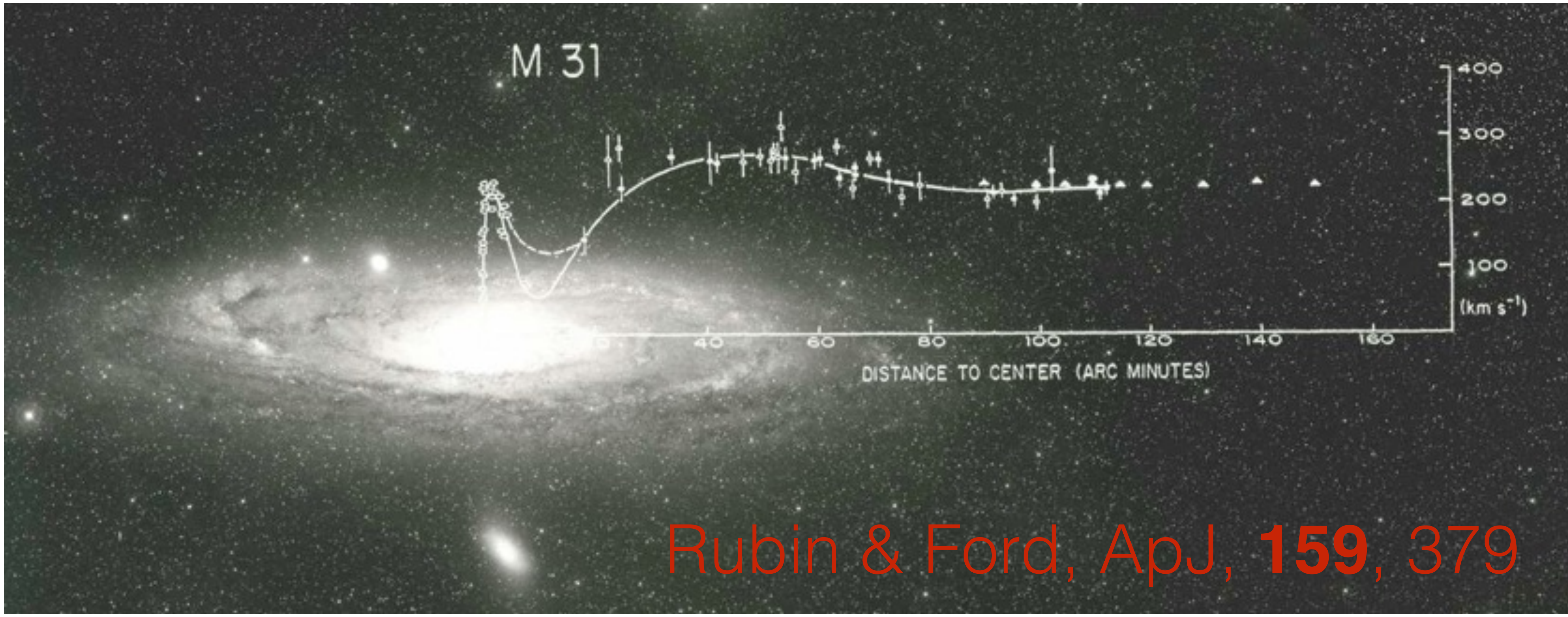
Describe connection between neutrinos and dark matter

What can we learn about this?

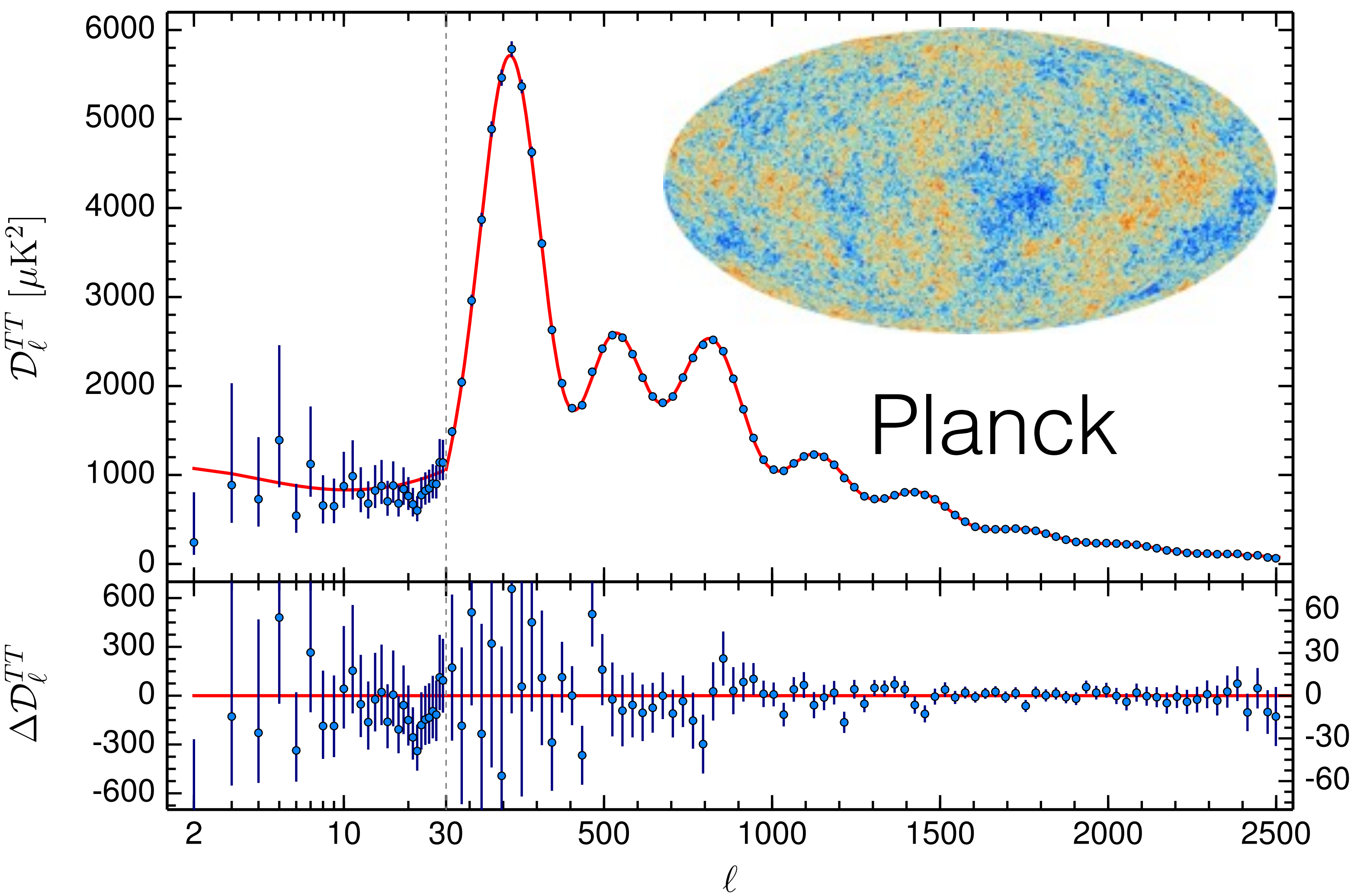
How neutrino experiments can help us search for DM

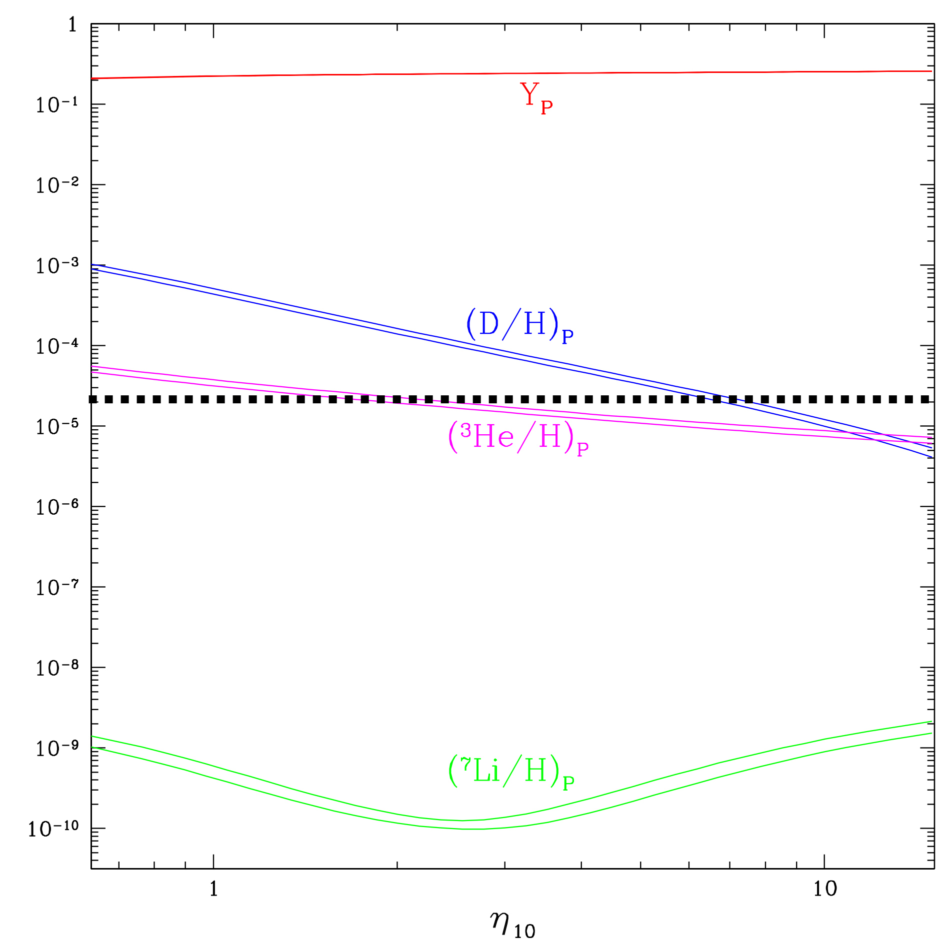
Briefly mention interplay between terrestrial & cosmological measurements of neutrino mass

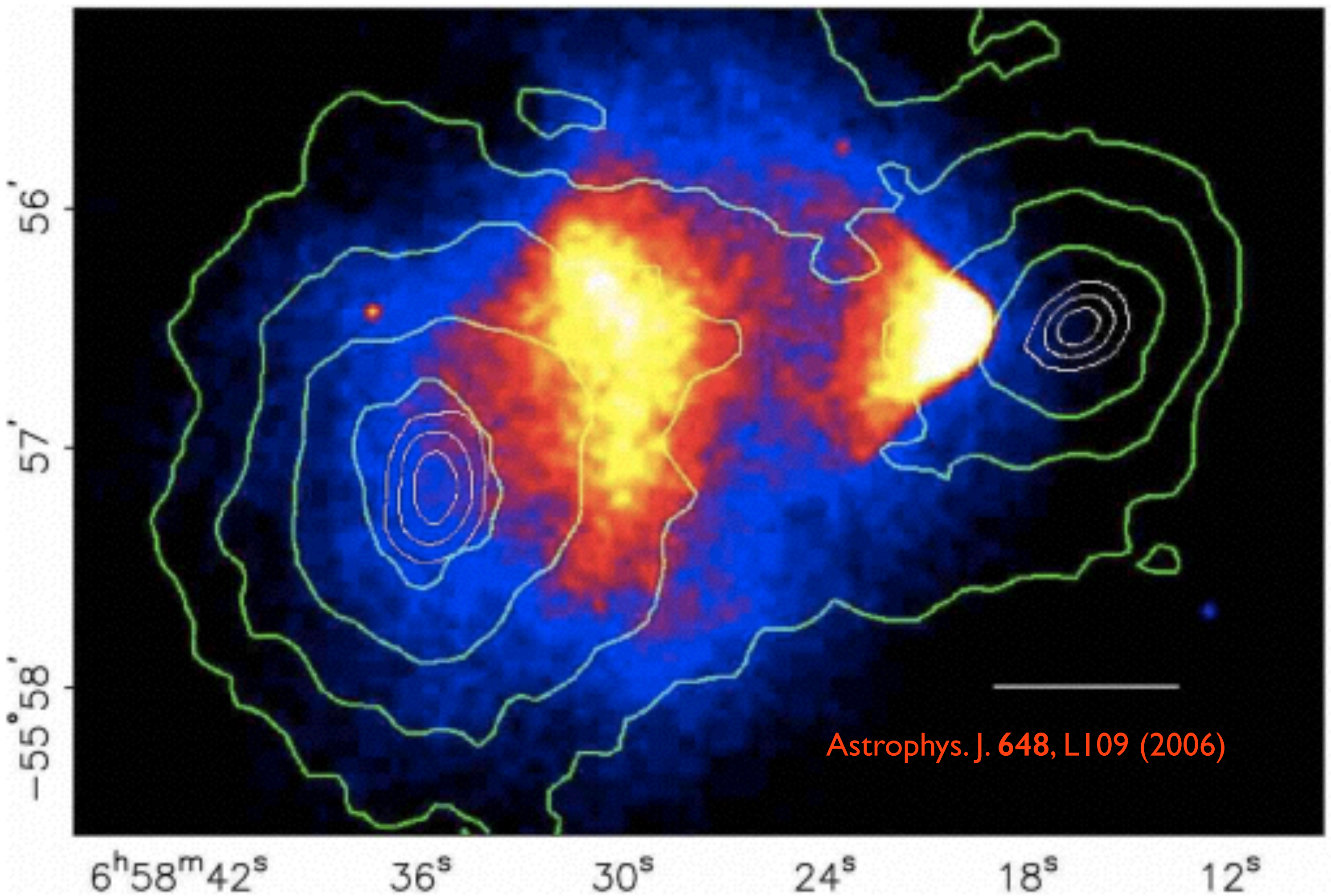
Another example of new physics: dark matter



Rubin & Ford, ApJ, **159**, 379

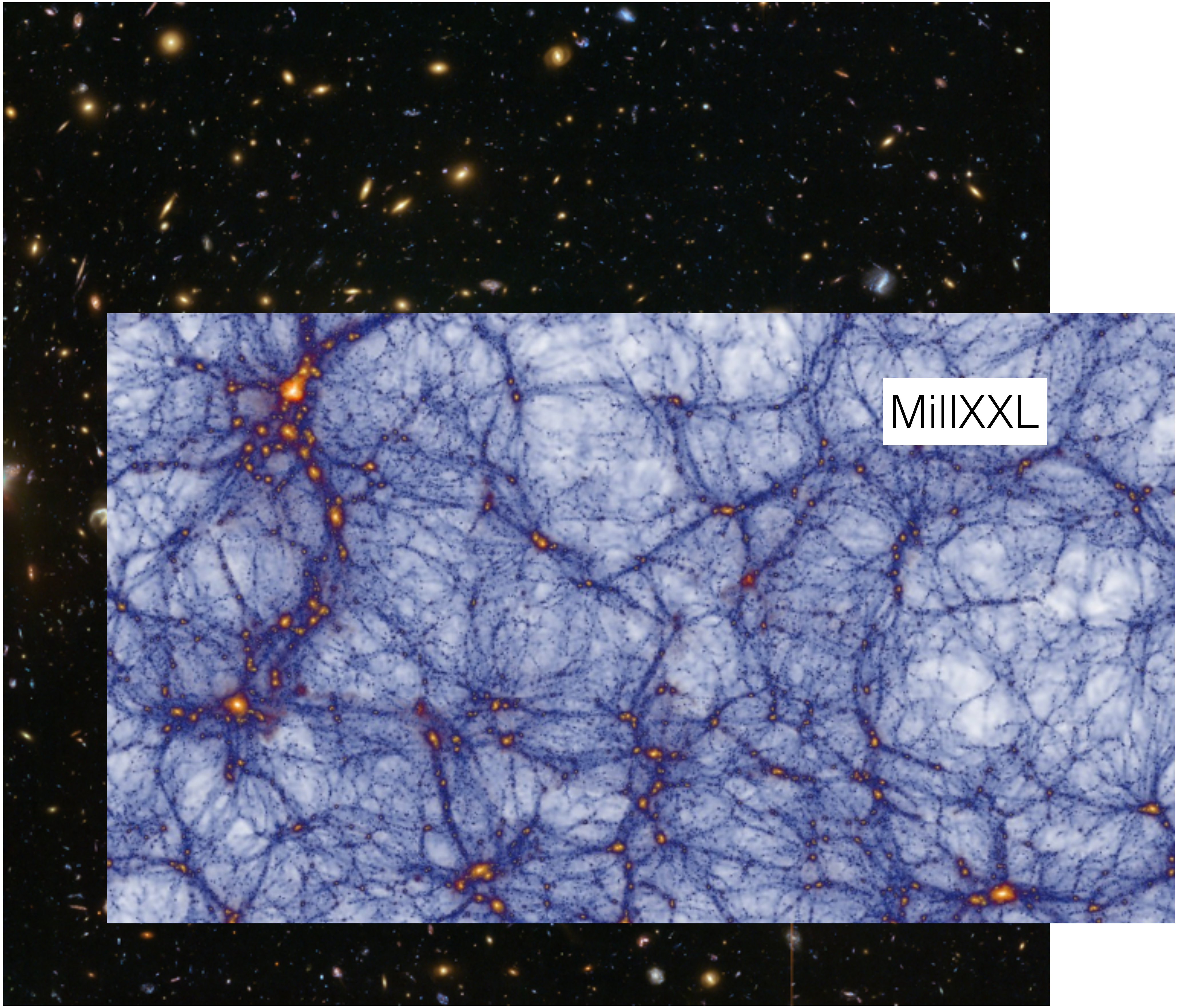




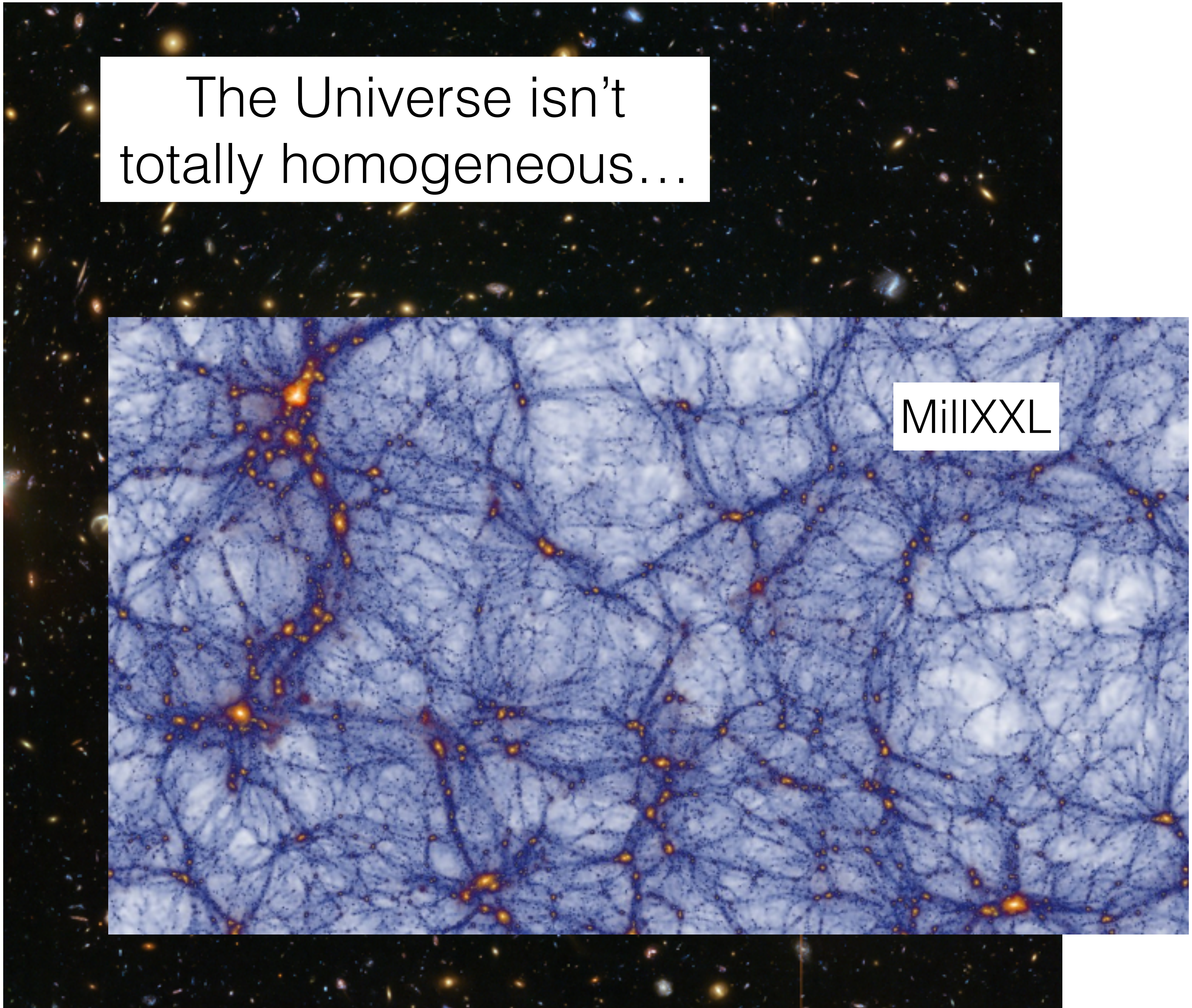

-55°58'
57'
56'
6h58m42s
36s
30s
24s
18s
12s
Astrophys. J. 648, L109 (2006)

General consensus on energy budget of Universe

So what can neutrinos tell us about DM?

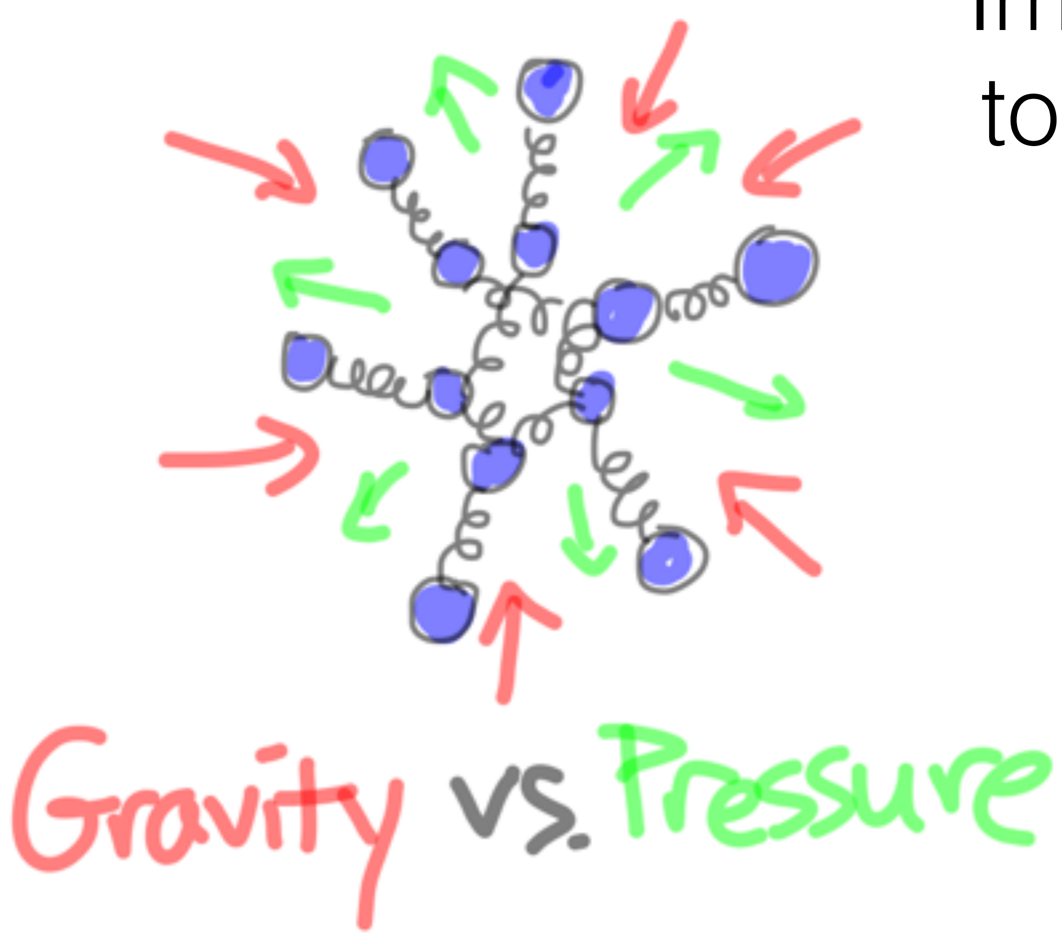

MillXXL

The Universe isn't totally homogeneous…



How does structure form?

Basic physics that sets the scales of structure formation



Imagine massive particles coupled to a light force (not gravity) carrier, i.e. radiation

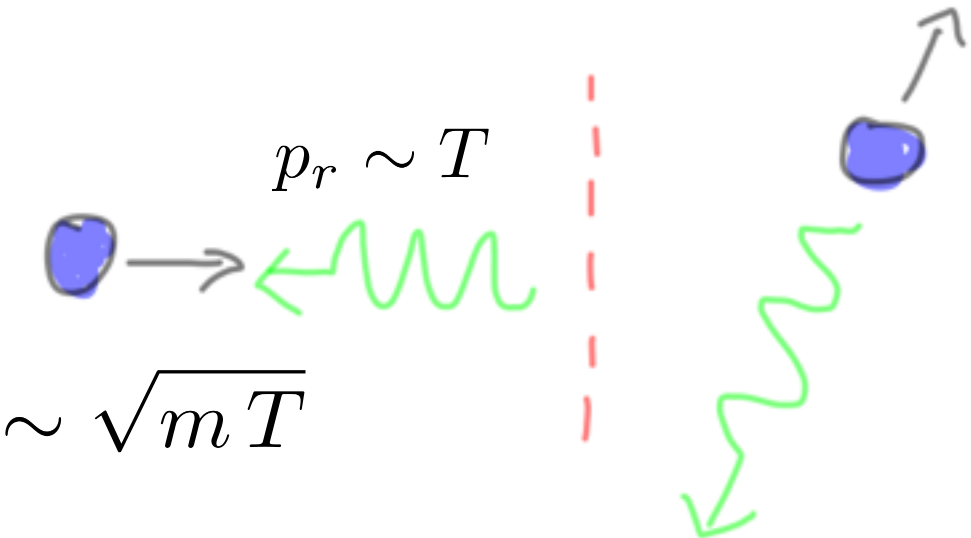
e.g. baryon collapse resisted by photons

structure starts to form when no pressure (i.e. particles decouple from force carrier)

structures smaller than horizon size at decoupling are suppressed

What is decoupling scale?

$p_r \sim T$



$p_m \sim \sqrt{mT}$

$(\Delta p_m)_1 \sim p_r \sim T$

How many scatters for O(1) momentum change?

$$(\Delta p_m)_N \sim \sqrt{N}\,(\Delta p_m)_1 \sim \sqrt{N}T$$

$$\Rightarrow N \sim \frac{m}{T}$$

Compare rate for N scatters to Hubble

$$\frac{n_r \sigma}{N} \sim \frac{T}{m} n_r \sigma \sim \frac{T^4}{m}\sigma > H$$

Given $\sigma = \dfrac{T^2}{\Lambda^4},\ H \propto \dfrac{T^2}{M_{\rm Pl}} \Rightarrow T_{\rm d} \sim \left(\dfrac{\Lambda^4 m_\chi}{M_{\rm Pl}}\right)^{1/4}$

Given T_{d} it's convenient to express a cutoff scale

$$M_{\mathrm{cut}} = \rho_m\left(T_d\right)\frac{4\pi}{3}H_d^{-3} \sim 10^8 M_{\odot}\left(\frac{T_d}{\mathrm{keV}}\right)^{-3}$$

Structures smaller than this are suppressed

Neutrinos actually first particle DM candidate [Cowsik, McClelland '72]

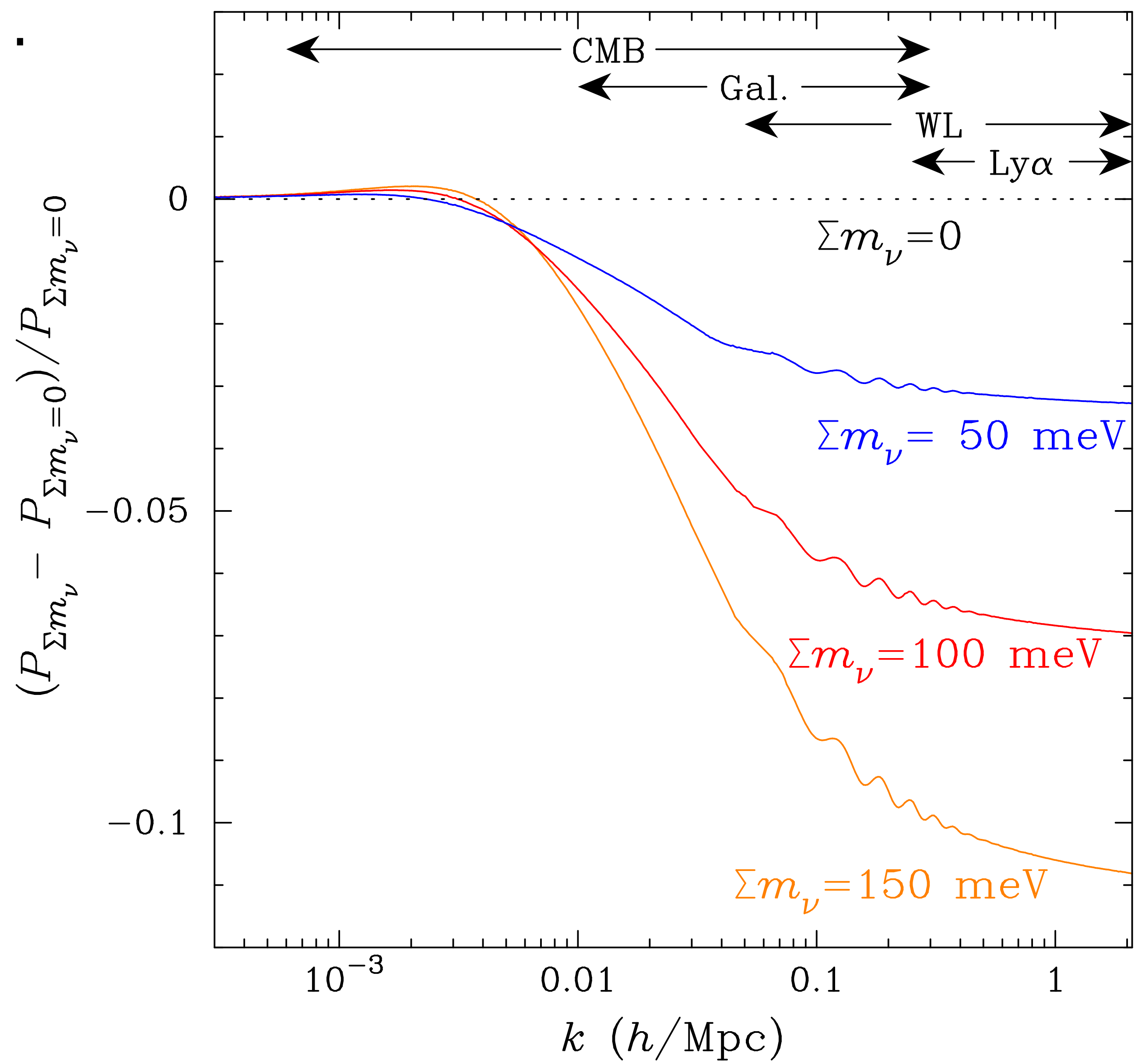
larger scales ⟵ ⟶ smaller scales

But neutrinos too hot…

Wash out structures ~horizon size (and smaller) at $T \sim m_\nu$

and too few…

$$\Omega_\nu h^2 \sim 10^{-2} \left(\frac{m_\nu}{\text{eV}}\right)$$



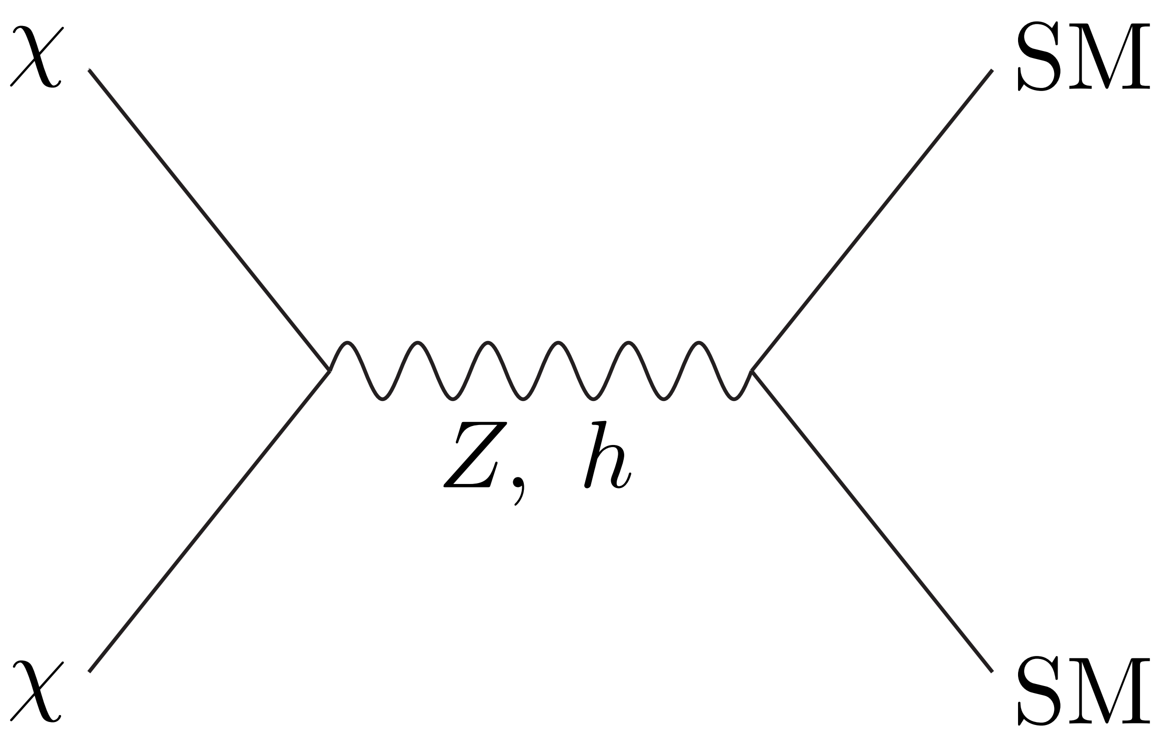
structure formation tells us neutrinos are not (all of the) dark matter

What cutoff scale do we expect?

Weakly Interacting Massive Particle

Stable, uncharged particle χ with mass roughly

$$m_\chi \sim m_Z,\ m_W,\ m_h \sim 100\ \mathrm{GeV/c^2}$$



Common in extensions of the Standard Model, e.g. SUSY, extra dims., …

Often easy to get correct DM abundance today

What does structure tell us about WIMP DM?

What decoupling temperature/cutoff scale do we expect for a WIMP?

Recall decoupling temp. is determined by interaction strength of DM with radiation

$$T_{\mathrm{d}} = \left(\frac{\Lambda^4 m_\chi}{M_{\mathrm{Pl}}} \right)^{1/4} \quad \text{with} \quad \sigma = \frac{T^2}{\Lambda^4}$$

Recall decoupling temp. is determined by interaction strength of DM with radiation

$$T_{\mathrm{d}} = \left(\frac{\Lambda^4 m_\chi}{M_{\mathrm{Pl}}}\right)^{1/4} \quad \text{with} \quad \sigma = \frac{T^2}{\Lambda^4}$$

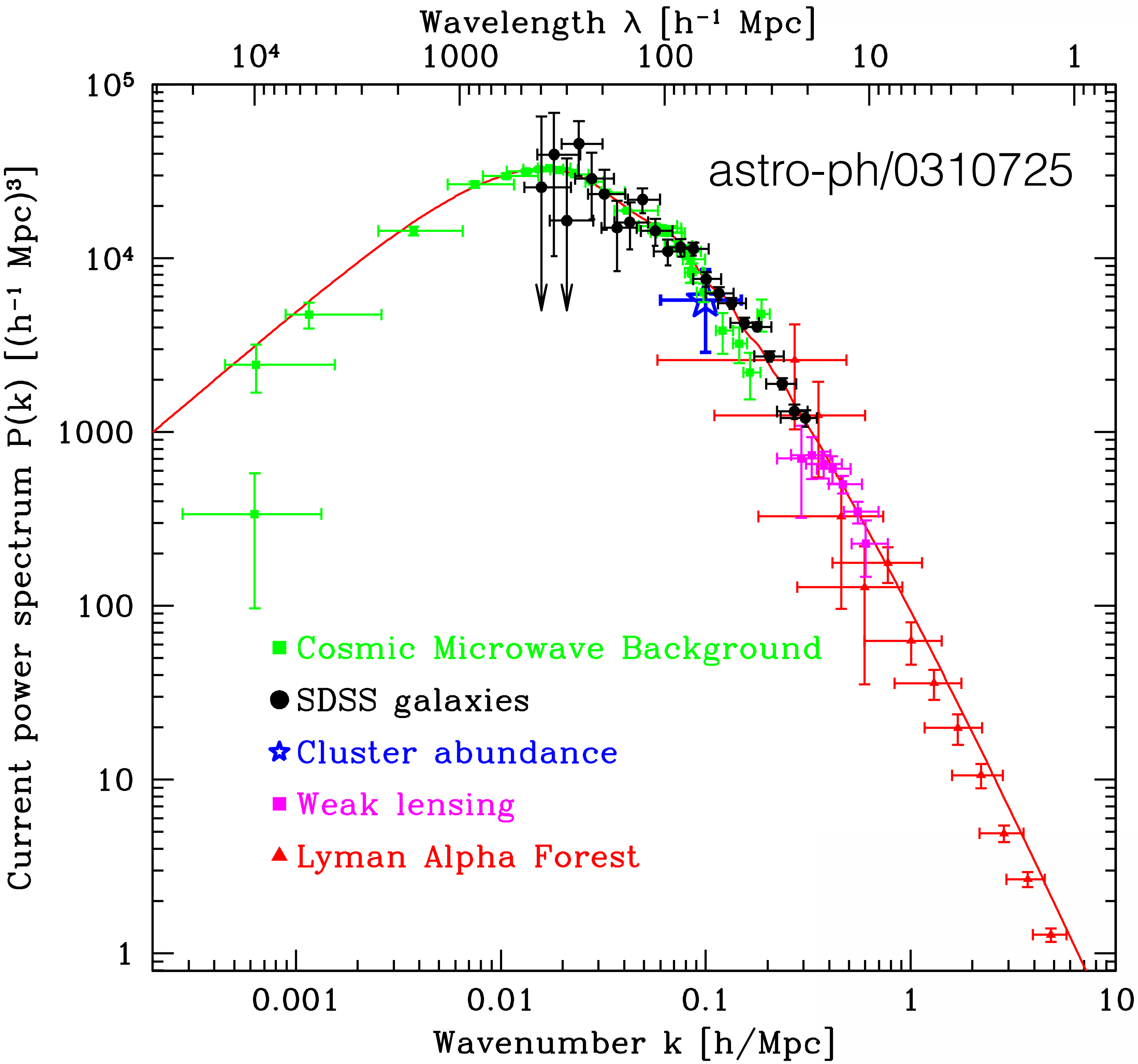
WIMP: ~100 GeV ➡ $T_{\mathrm{d}} \sim 10\ \mathrm{MeV}$

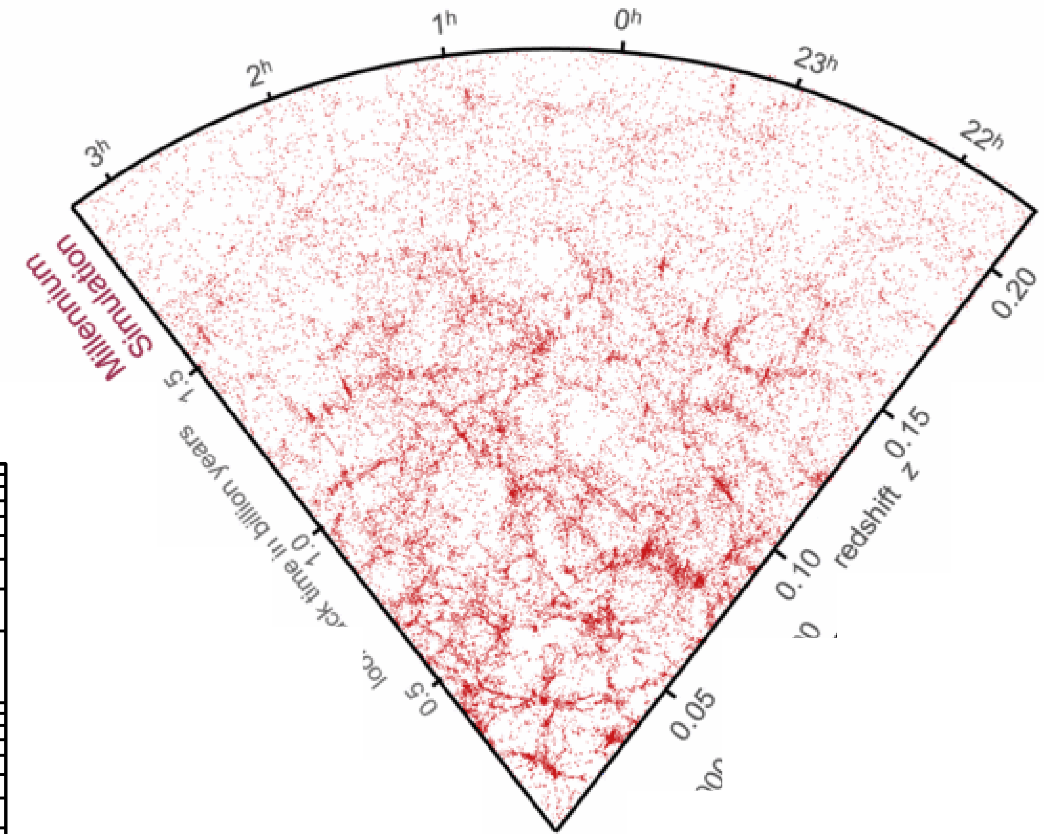
➡ $M_{\mathrm{cut}} \sim 10^8 M_\odot \left(\frac{T_d}{\mathrm{keV}}\right)^{-3} \ll M_\odot$

i.e. WIMP DM should behave as if non-interacting for structure down to smallest observable scales

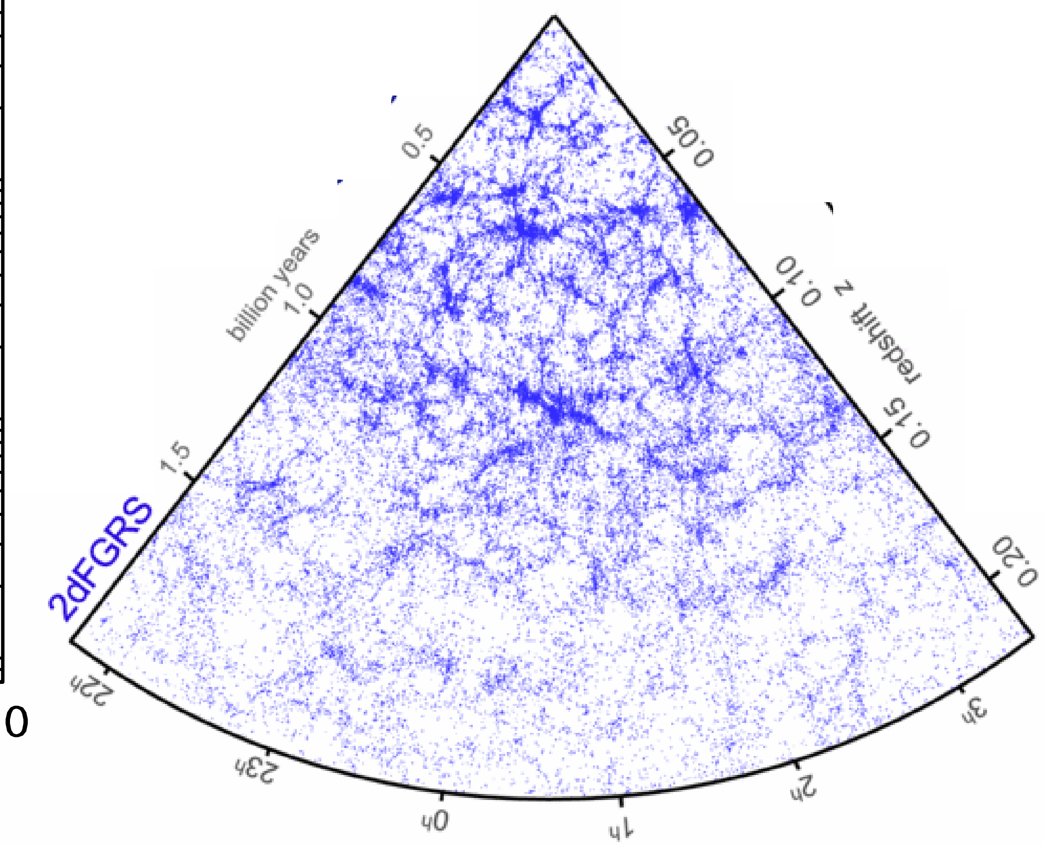
What does the data say?

Large Scales Look Good for WIMPs

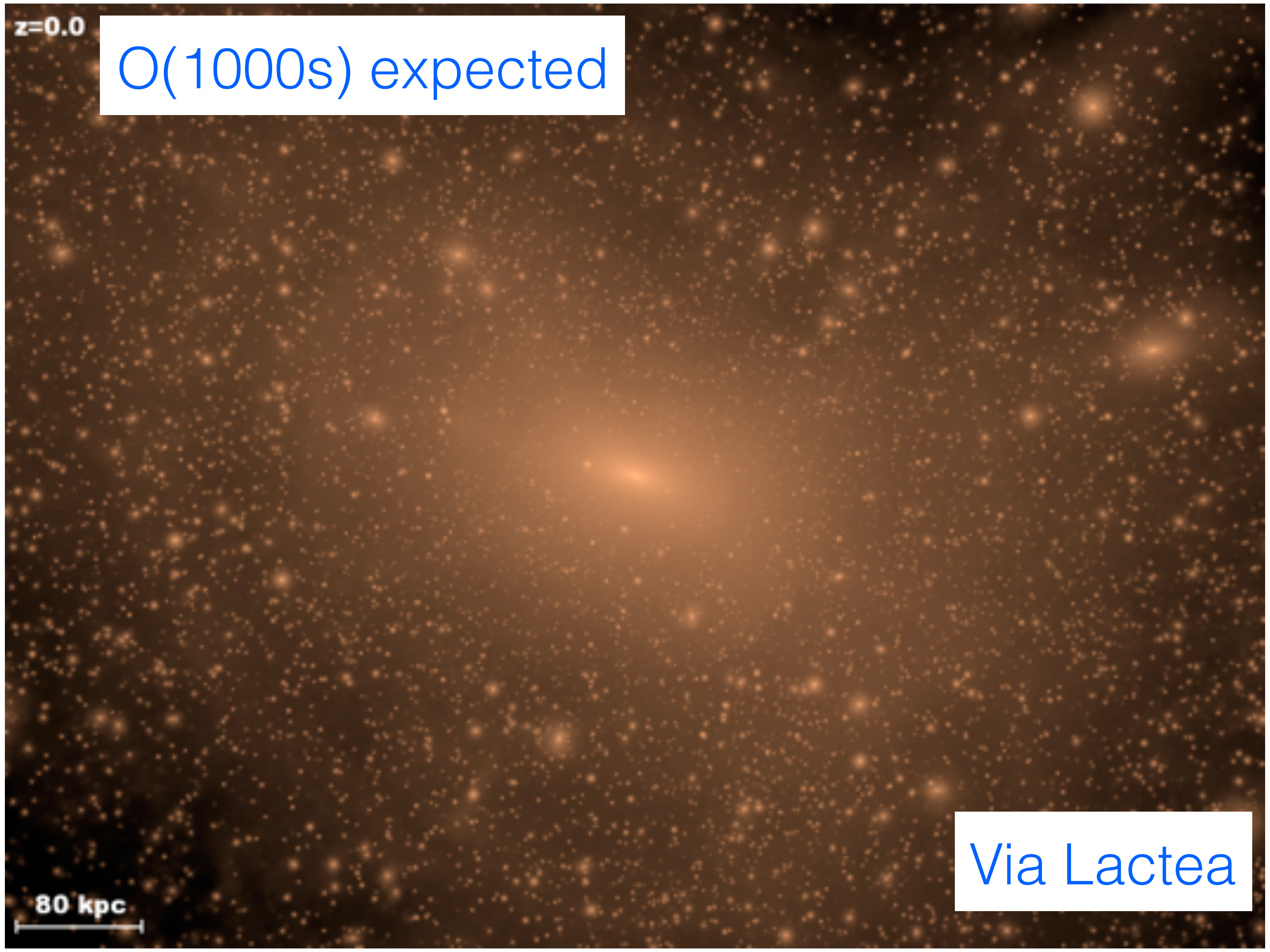




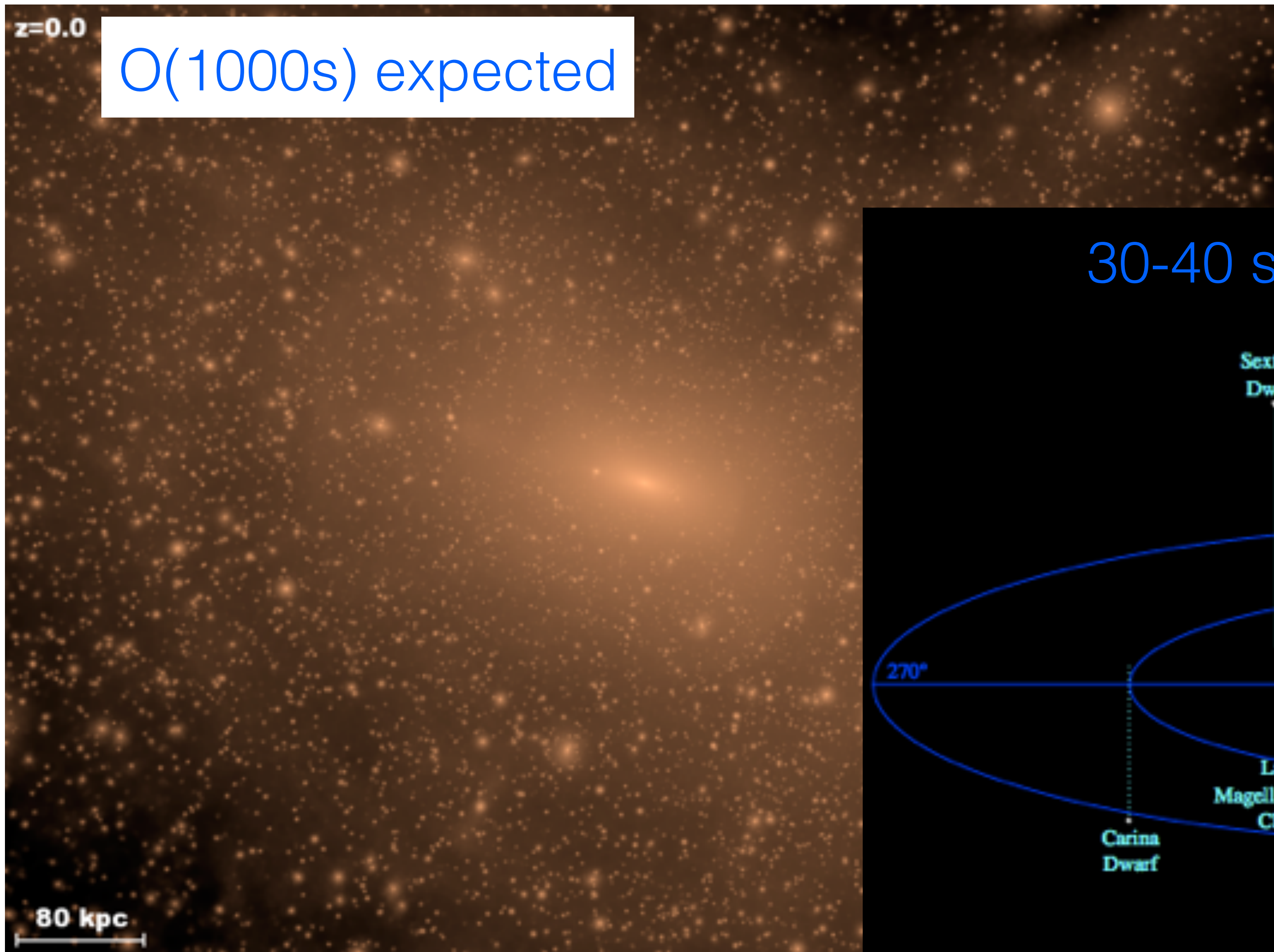
astro-ph/0604561

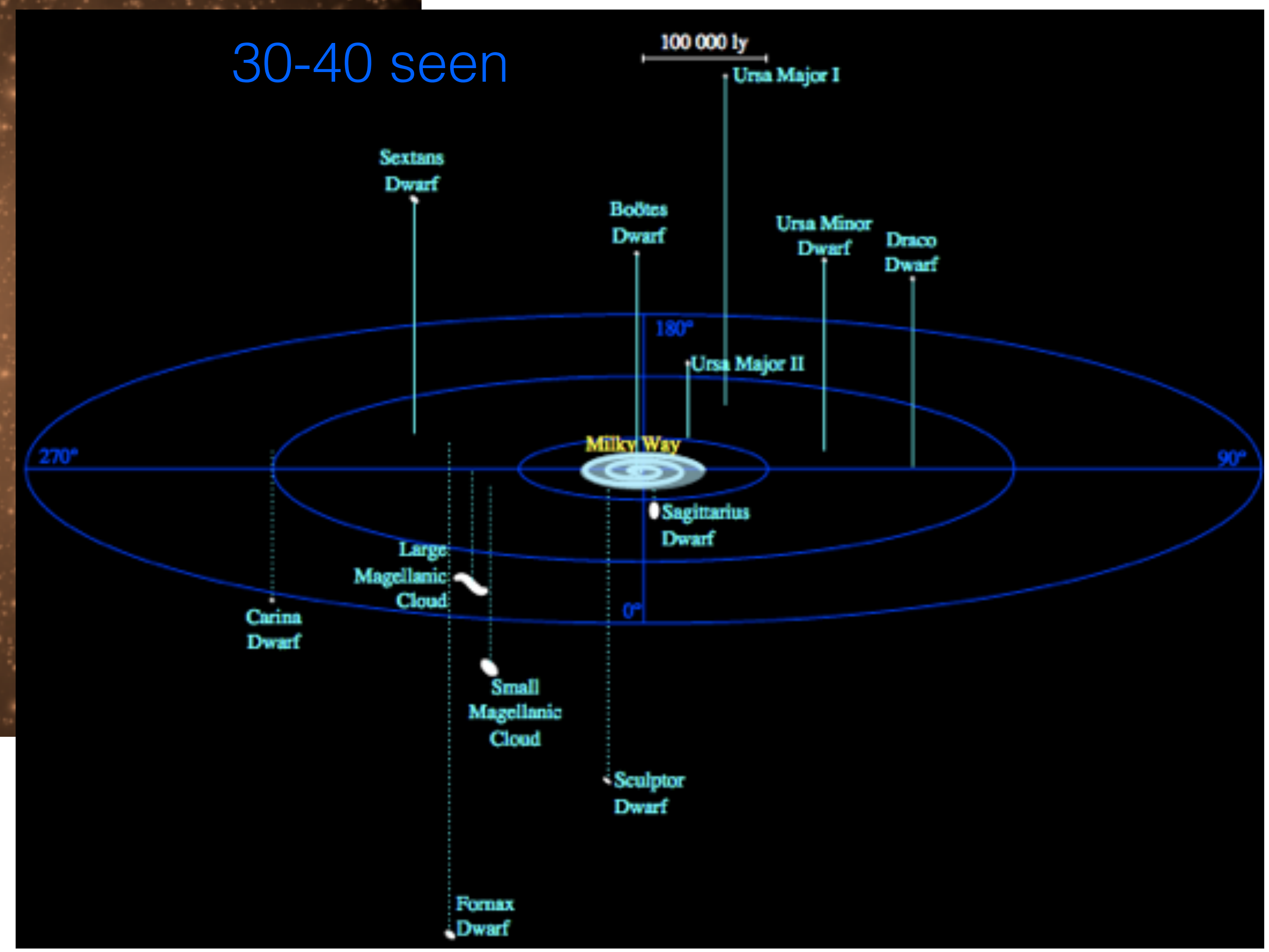


Count satellites of Milky Way-like galaxy



Count satellites of Milky Way-like galaxy

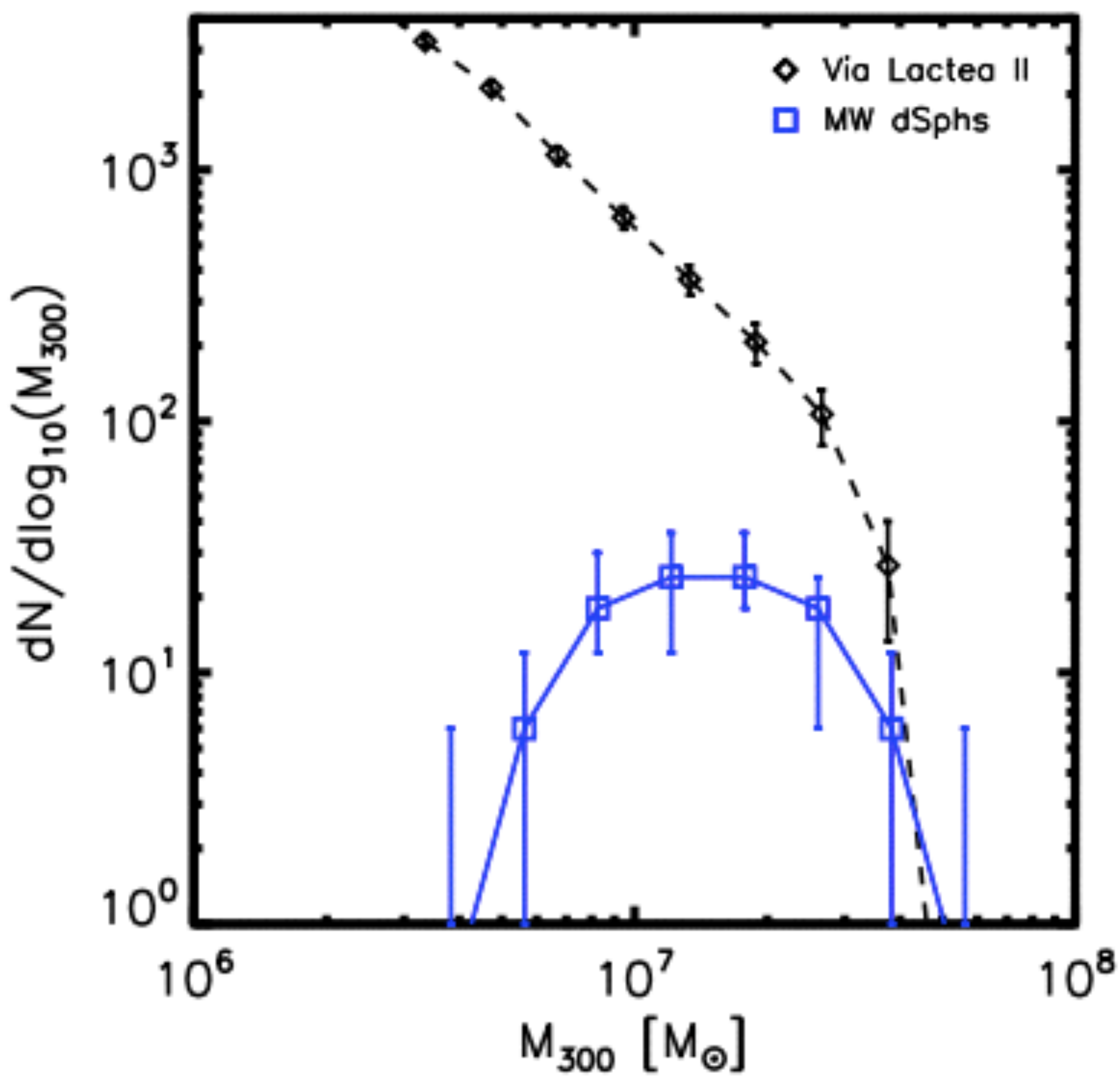




Count satellites of Milky Way galaxy

Bullock, arXiv:1009.4505

Compared to expectation, fewer small halos orbiting Milky Way-sized galaxy

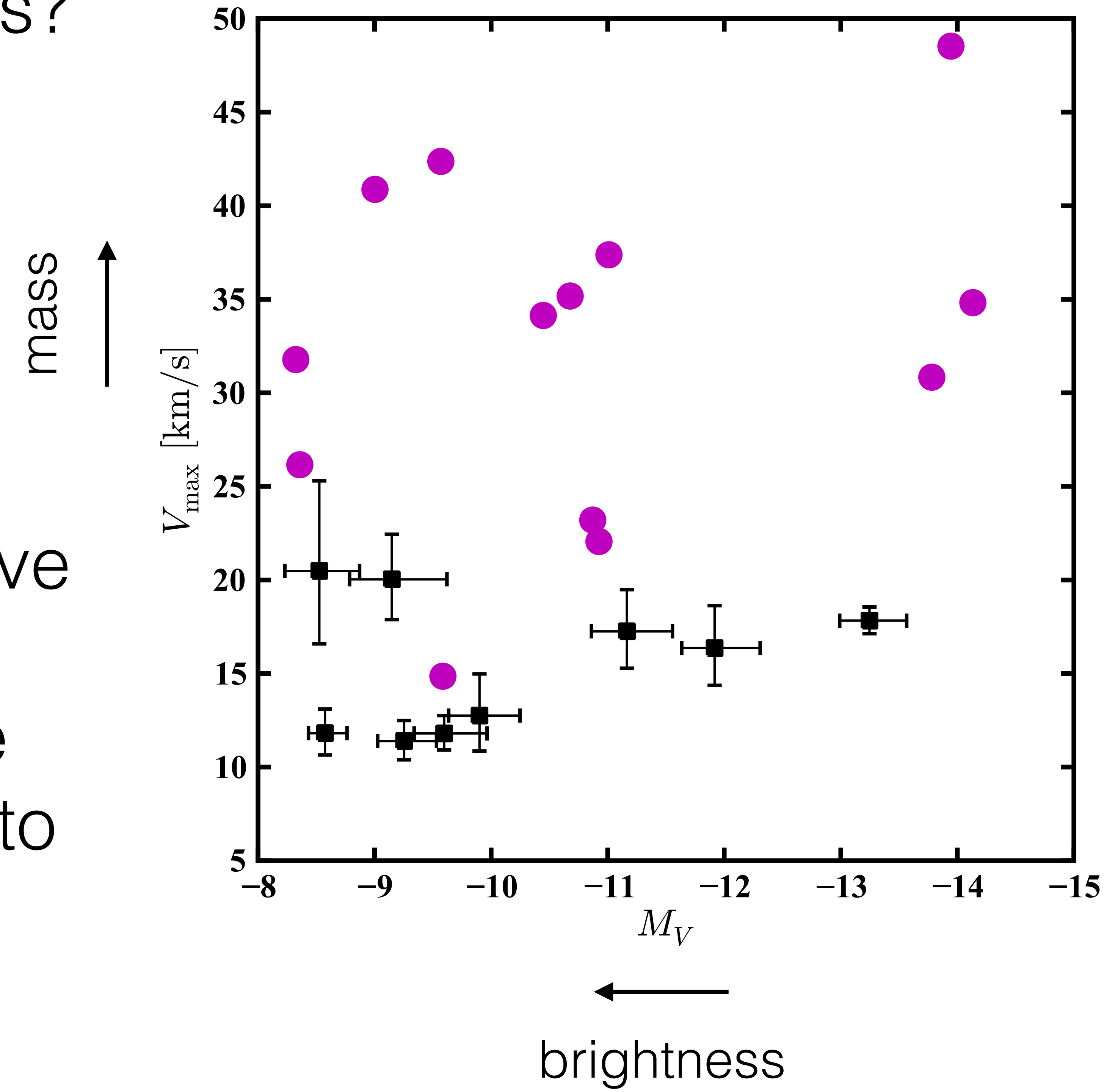


"Missing Satellites"

Suggestive of a cut off $M_{cut} \sim 10^{7\text{-}9}\ M_\odot$, much larger than WIMP case

Could be selection bias?

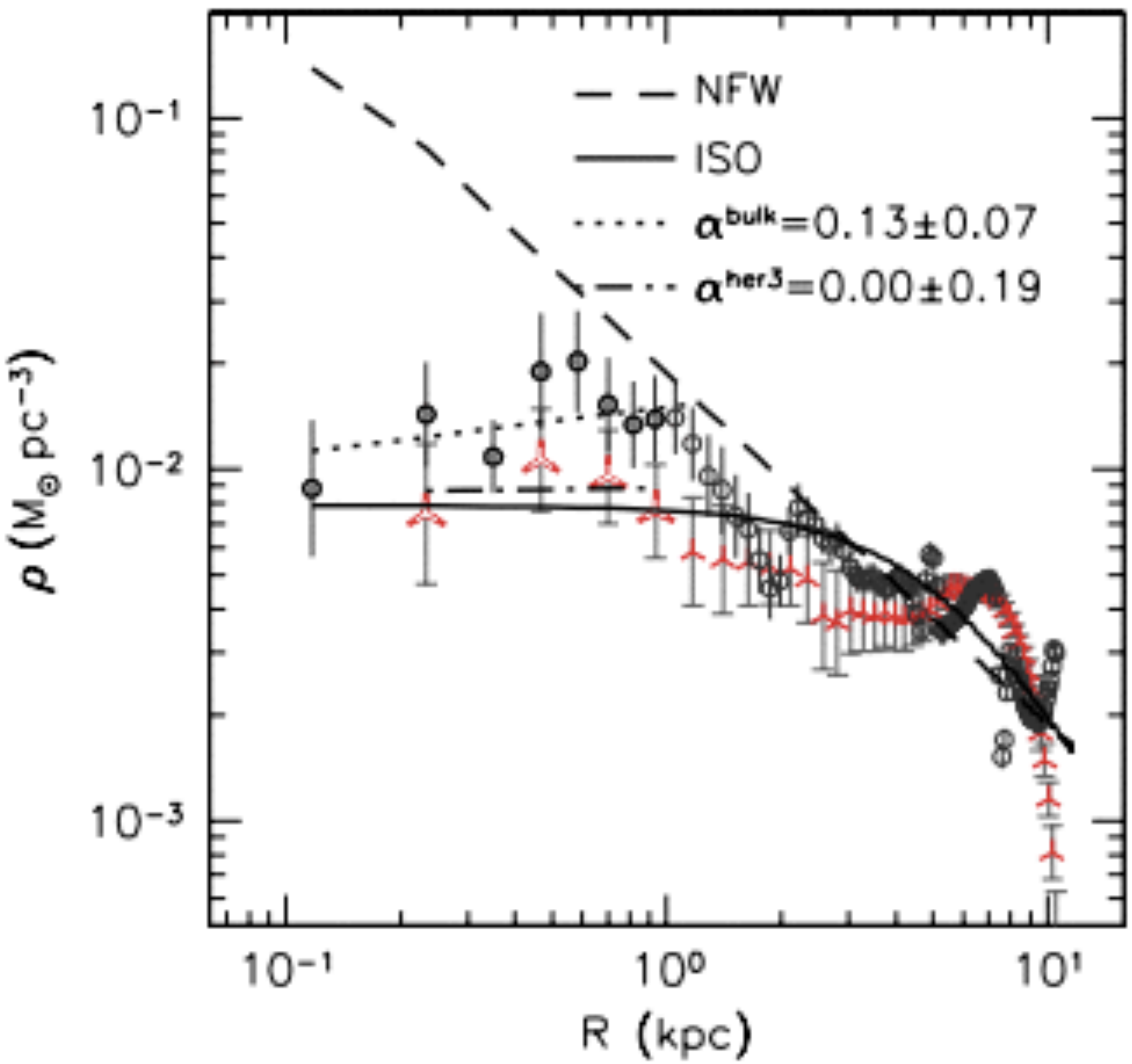
Boylan-Kolchin, Bullock, Kaplinghat, arXiv:1111.2048



N-body simulations indicate that most massive MW satellites more massive than those we know, i.e. large enough to form stars

"Too Big to Fail"

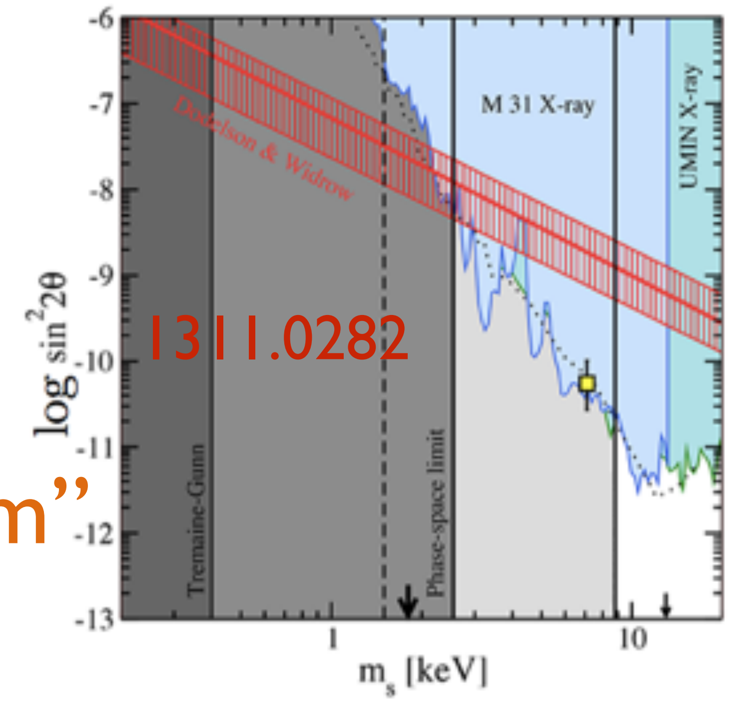
Oh *et al.*, arXiv:1011.0899



DM density profiles appear flatter, less cuspy at center than expected

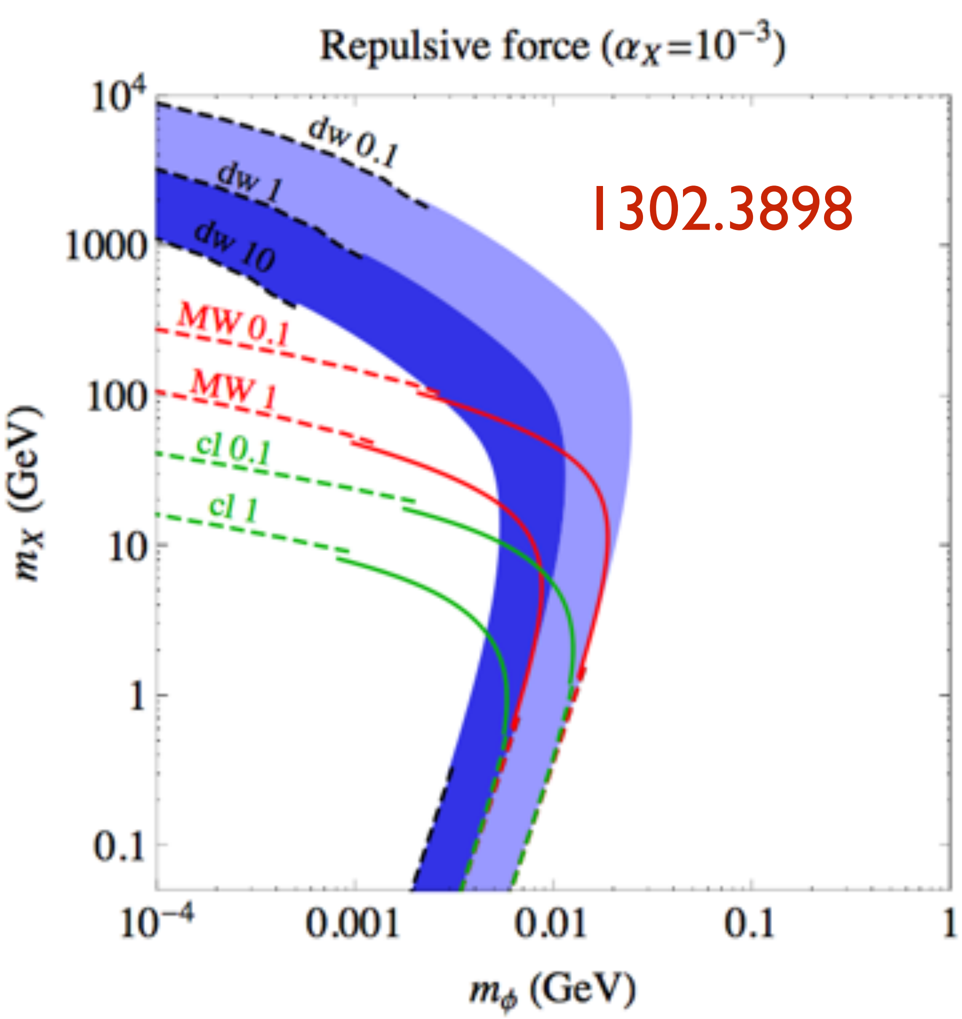
"Core vs. Cusp"

Potential Resolutions



Could be fixed by baryonic effects

(Brooks, Governato, Pontzen, ++)



DM could be "warm"

(Abazajian, Horiuchi, ++)

DM could self-interact

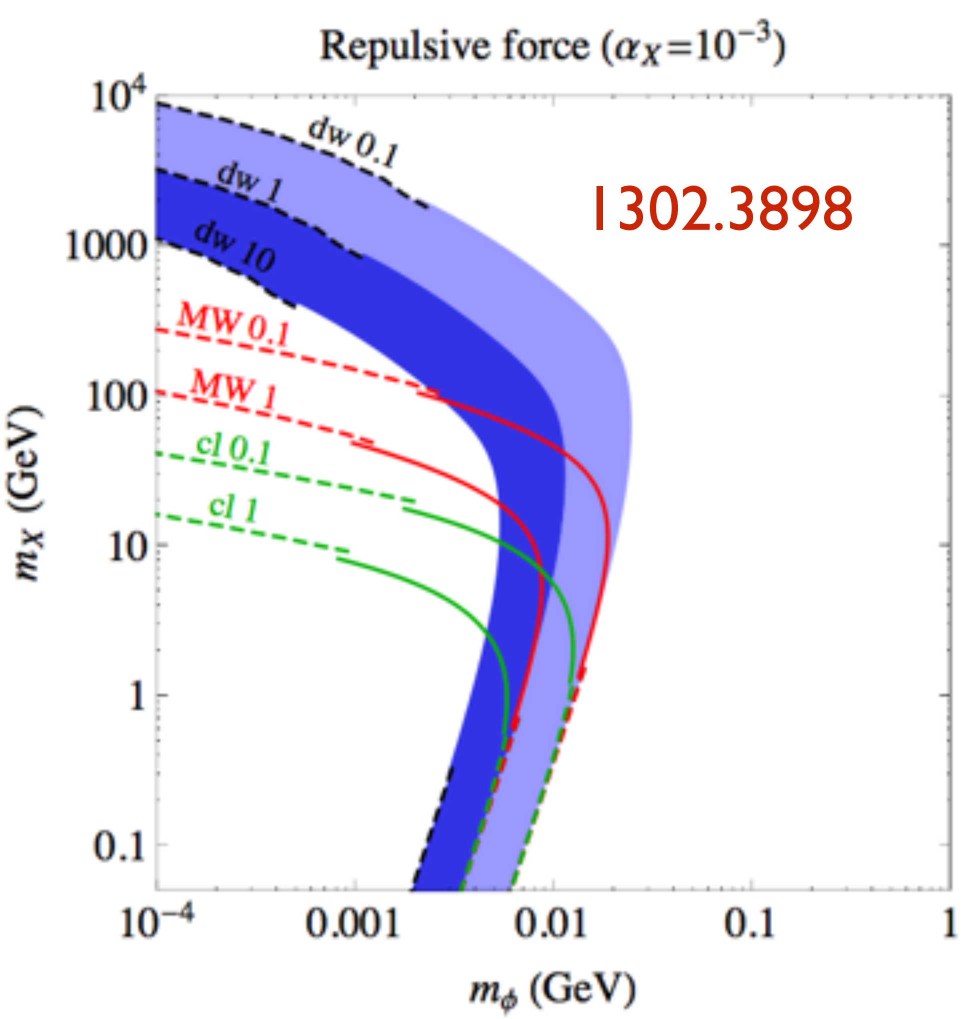
(Spergel, Steinhardt; Hai-Bo Yu, Tulin, Zurek, ++)

DM could interact with the plasma

Potential Resolutions

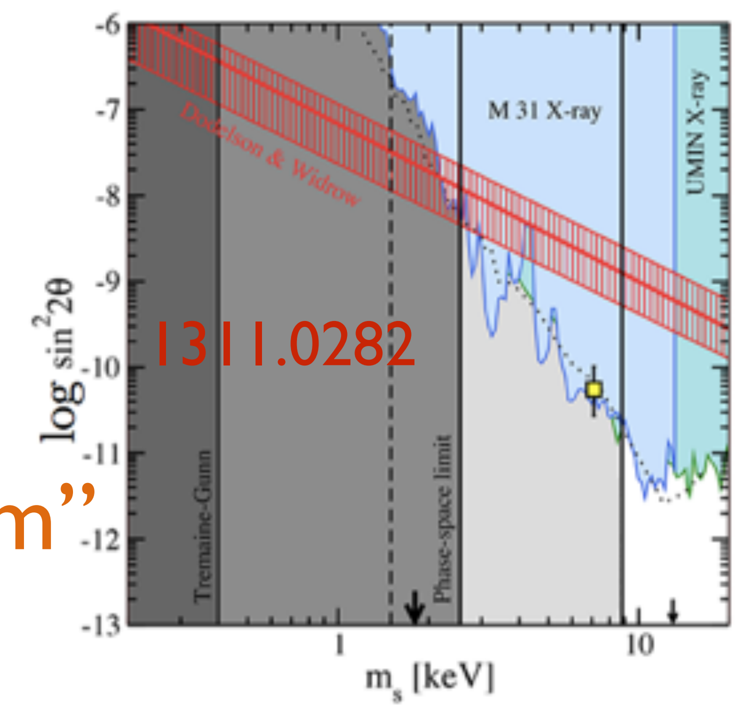
Could be fixed by baryonic effects

(Brooks, Governato, Pontzen, ++)



DM could be "warm"

(Abazajian, Horiuchi, ++)



DM could self-interact

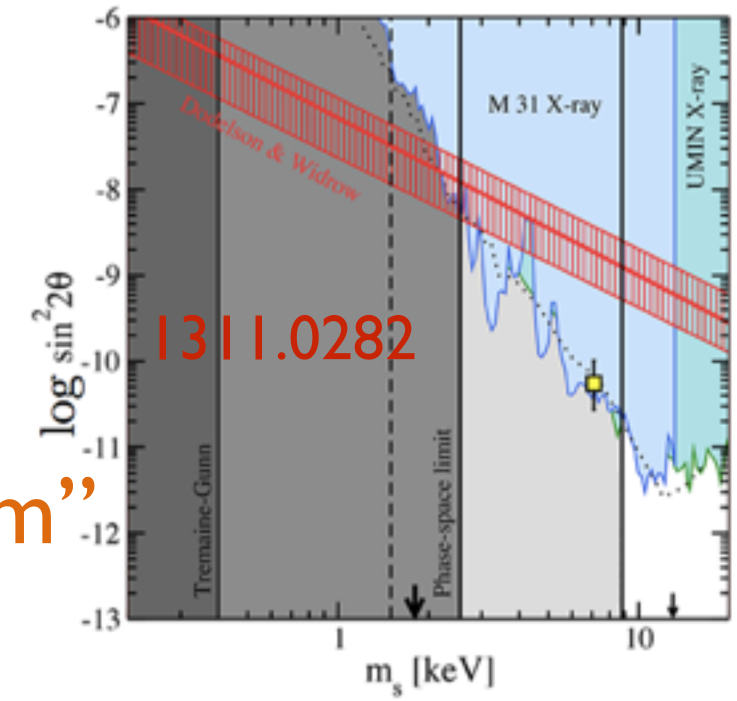
(Spergel, Steinhardt; Hai-Bo Yu, Tulin, Zurek, ++)

DM could interact with the plasma

Potential Resolutions

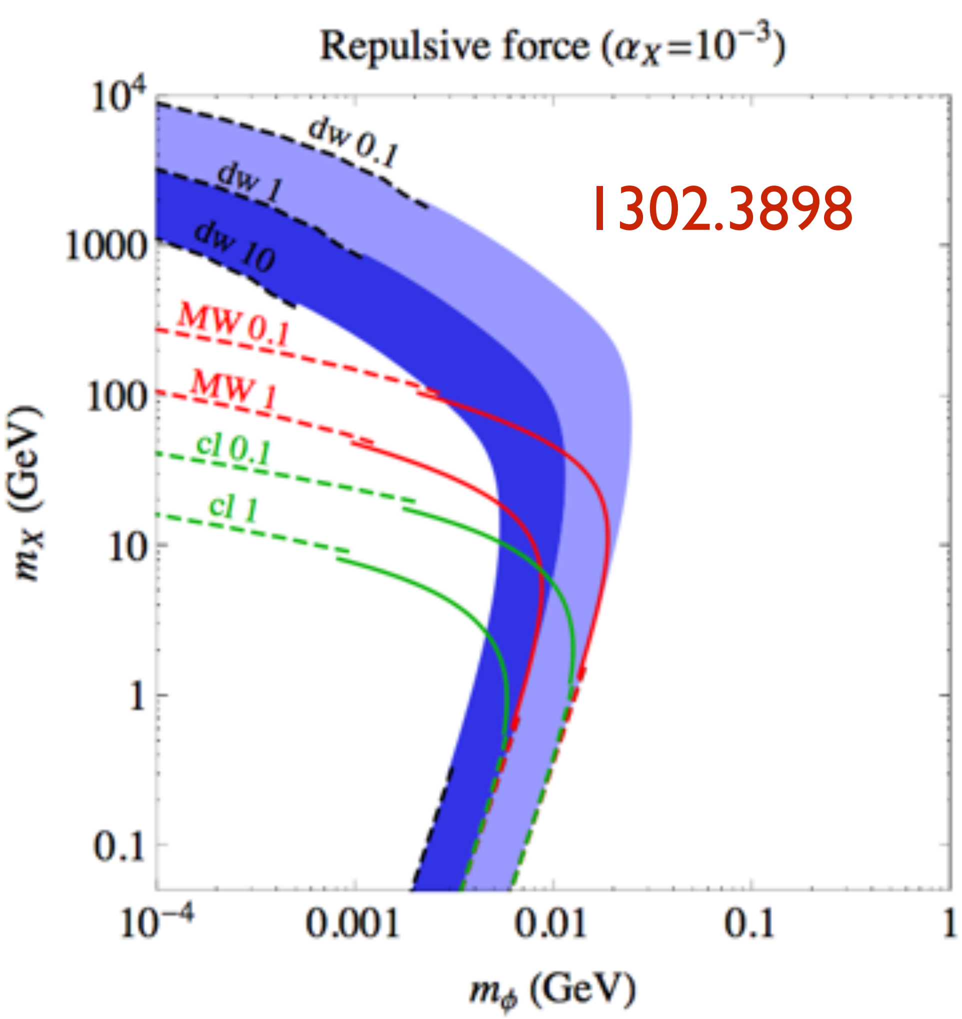
Could be fixed by baryonic effects

(Brooks, Governato, Pontzen, ++)



DM could be "warm"

(Abazajian, Horiuchi, ++)



DM could self-interact

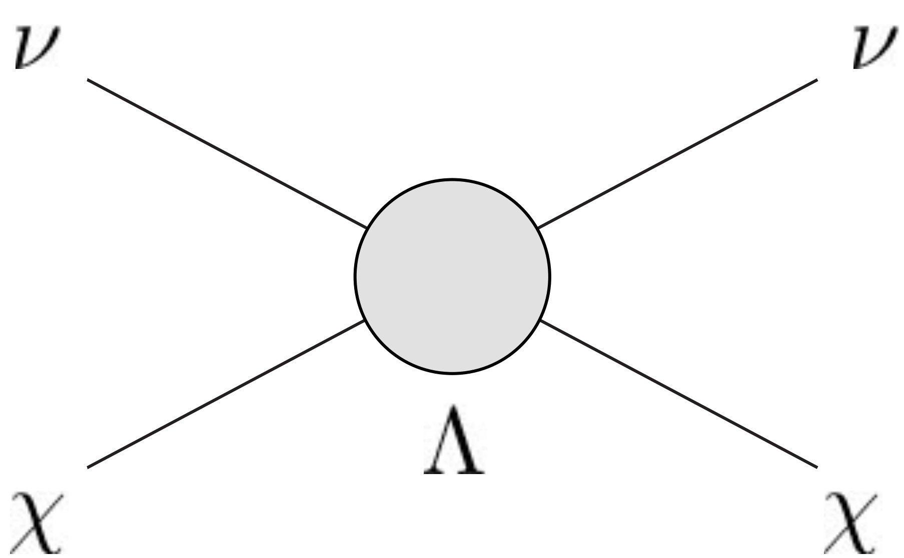
(Spergel, Steinhardt; Hai-Bo Yu, Tulin, Zurek, ++)

DM could interact with the plasma

Back to neutrinos…

Boehm, Ma, et al.
Shoemaker, 1305.1936
van den Aarssen et al., 1205.5809
Macias, Wudka …

Recall $M_{\mathrm{cut}} \sim 10^8 M_\odot \left(\frac{T_{\mathrm{d}}}{\mathrm{keV}}\right)^{-3}$ so want $T_{\mathrm{d}} \sim \mathrm{keV}$



$$\mathcal{L}_{\mathrm{eff}} = \frac{1}{\Lambda^2}\bar{\nu}\nu\bar{\chi}\chi \Rightarrow \sigma = \frac{T^2}{\Lambda^4}$$

then $T_d \sim \left(\frac{\Lambda^4 m_\chi}{M_{\mathrm{Pl}}}\right)^{1/4} \sim \mathrm{keV}$

if $\Lambda^4 m_\chi \sim (100\ \mathrm{MeV})^5$

(Note: large annihilation cross section implies asymmetric DM)

EFT analysis highlights a small energy scale

Need to build a model!

Model Building at Low Energy Scales

Standard Model symmetries $$SU(3)_c \times SU(2)_L \times U(1)_Y \to SU(3)_c \times U(1)_{\rm em}$$

Standard Model particle content

$$\left.\begin{array}{ll} \ell = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} & e_R \\ & \\ q = \begin{pmatrix} u_L \\ d_L \end{pmatrix} & u_R \;\; d_R \end{array}\right\} \times 3$$

$$H = \begin{pmatrix} \rho^+ \\ v + h + \rho^0 \end{pmatrix} \qquad G^a_\mu,\; W^b_\mu,\; B_\mu \to G^a_\mu,\; A_\mu$$

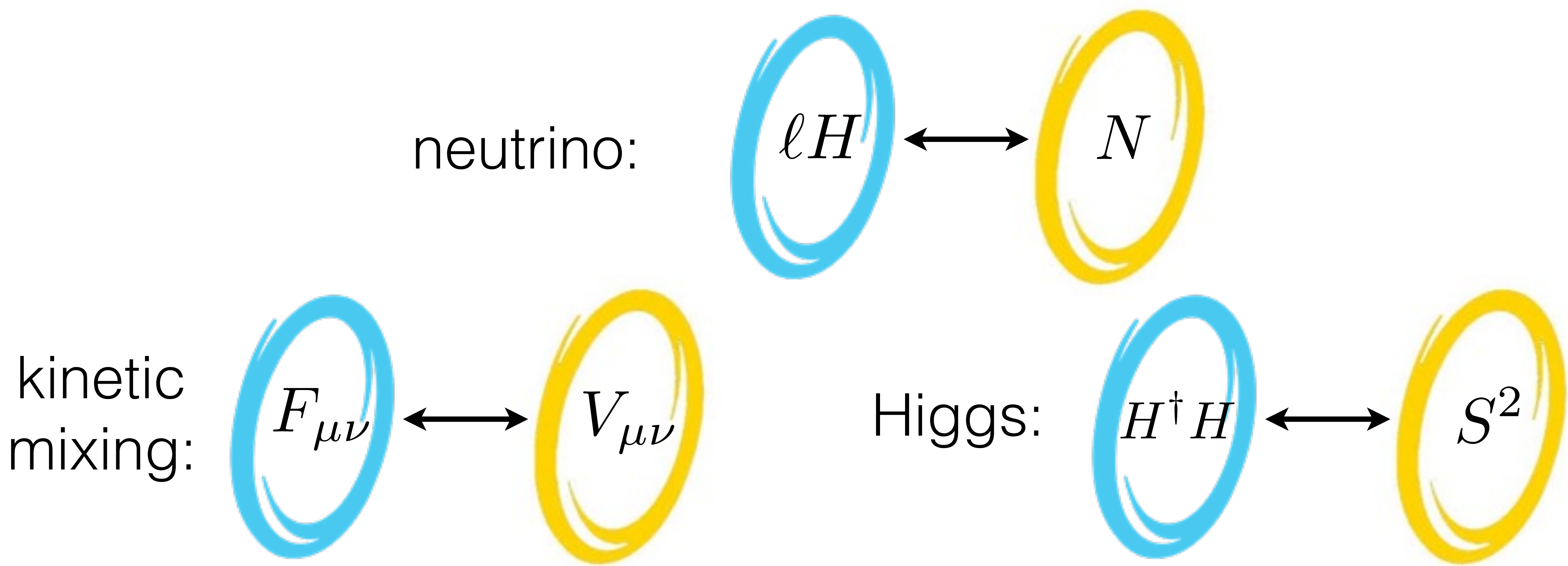
Renormalization: lower dim. operators (fewer fields/particles) more important

Model Building at Low Energy Scales

Standard Model symmetries $SU(3)_c \times SU(2)_L \times U(1)_Y \to SU(3)_c \times U(1)_{\rm em}$

Portals: coupling via stuff uncharged w.r.t. SM

Lead to minimal difficulties incorporating hidden sectors

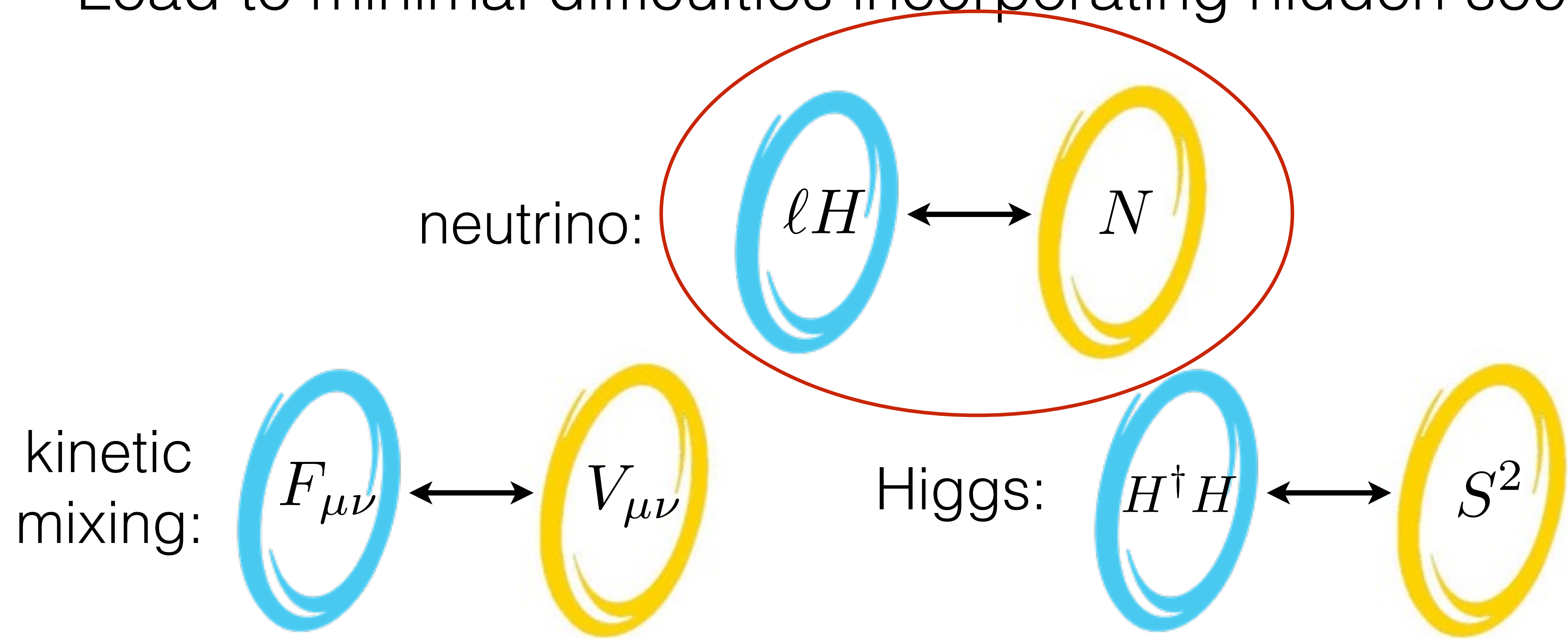


Model Building at Low Energy Scales

Standard Model symmetries $$SU(3)_c \times SU(2)_L \times U(1)_Y \to SU(3)_c \times U(1)_{\rm em}$$

Portals: coupling via stuff uncharged w.r.t. SM

Lead to minimal difficulties incorporating hidden sectors



Model Building at Low Energy Scales

Standard Model symmetries $SU(3)_c \times SU(2)_L \times U(1)_Y \to SU(3)_c \times U(1)_{\rm em}$

Portals: coupling via stuff uncharged w.r.t. SM

Lead to minimal difficulties incorporating hidden sectors

neutrino: $\ell H \longleftrightarrow N$

(likely already used: neutrino masses)

kinetic mixing: $F_{\mu\nu} \longleftrightarrow V_{\mu\nu}$

Higgs: $H^\dagger H \longleftrightarrow S^2$

Minimal Model

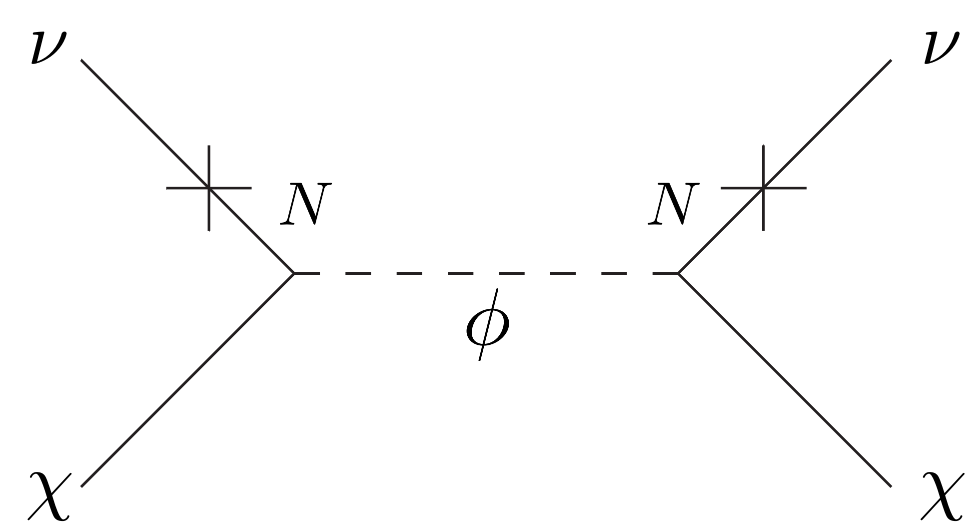
Simply coupling DM to the "neutrino portal" $\ell H \chi$ leads to DM decay

Can avoid with 2 new particles N, ϕ

χ and ϕ have "dark charge"

$$\mathcal{L} \supset -\frac{m_{ij}}{v^2}\left(H\ell_i\right)\left(H\ell_j\right) - \underbrace{M N_1 N_2 - \lambda_i N_1 H \ell_i - y_1 \phi^* N_1 \chi - y_2 \phi N_2 \chi}_{\text{lepton number conserved (for small v masses \& large mixing)}} + \text{h.c.}$$

Effective neutrino-DM interaction generated

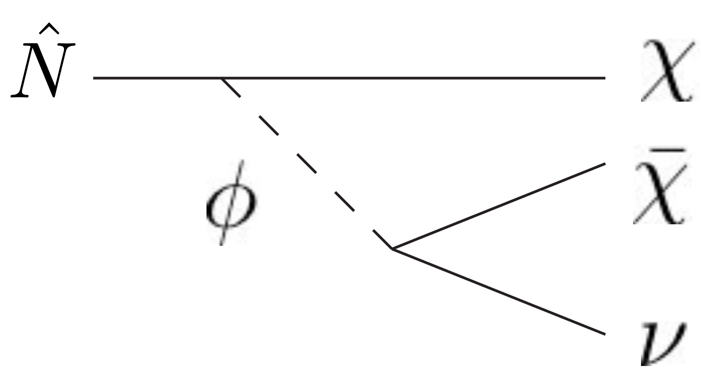


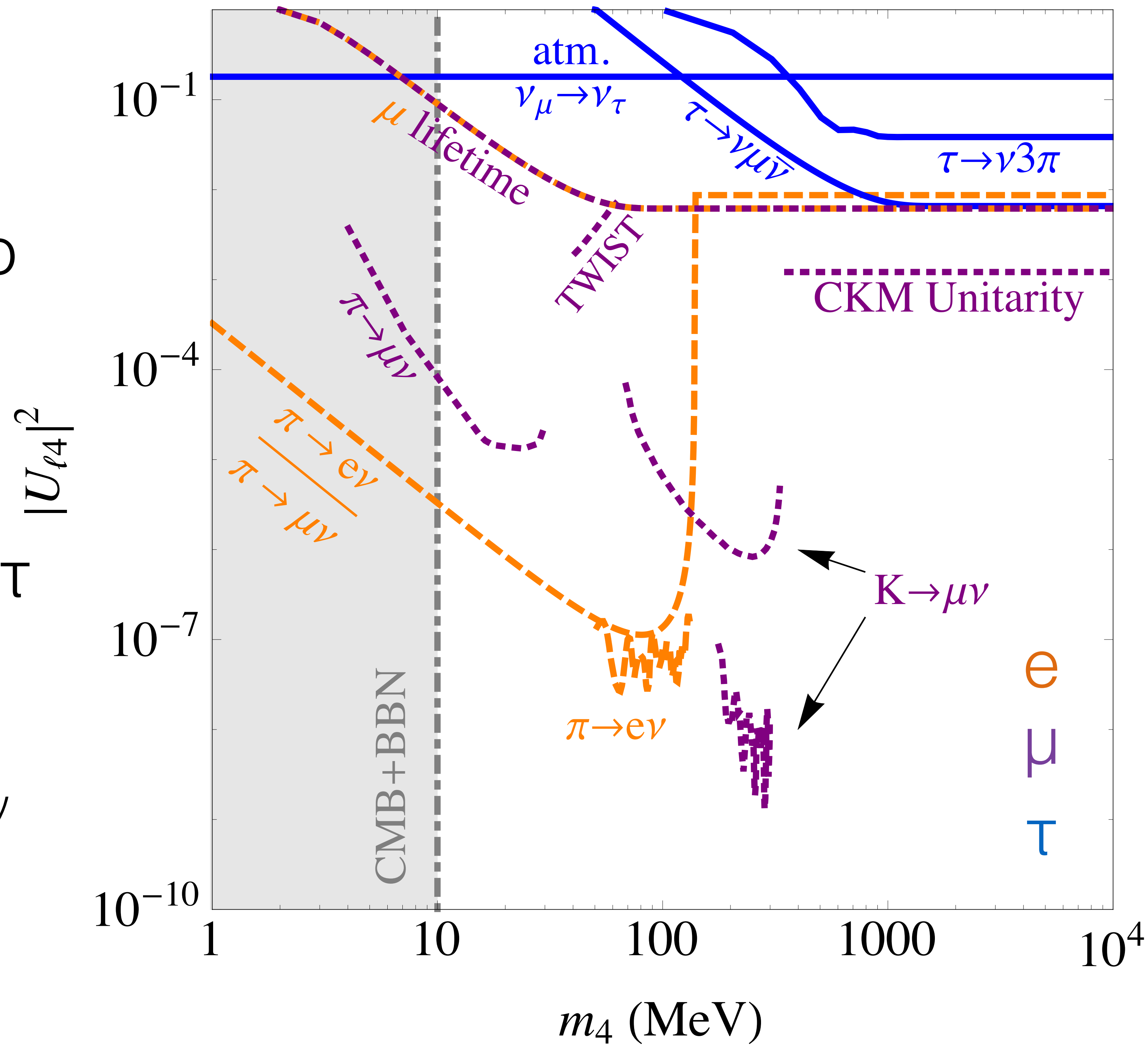
DM coupling to each neutrino flavor determined by mixing angle with sterile neutrino

Mixing angle affects known known neutrino properties

Strong limits on e, μ single out mixing with τ as promising

[Note: heavy (mostly sterile) ν decays invisibly]





Neutrino Oscillations

Assume mixing is dominantly with τ, just 1 more mixing angle in addition to the usual 3, and just 1 more (large) mass splitting

$$U = \begin{pmatrix} U^{3\times3}_{e1} & U^{3\times3}_{e2} & U^{3\times3}_{e3} & 0 \\ U^{3\times3}_{\mu1} & U^{3\times3}_{\mu2} & U^{3\times3}_{\mu3} & 0 \\ c_\theta U^{3\times3}_{\tau1} & c_\theta U^{3\times3}_{\tau2} & c_\theta U^{3\times3}_{\tau3} & s_\theta \\ -s_\theta U^{3\times3}_{\tau1} & -s_\theta U^{3\times3}_{\tau2} & -s_\theta U^{3\times3}_{\tau3} & c_\theta \end{pmatrix}$$

Recall

$|U_{e2}|^2, |U_{\mu2}|^2 + |U_{\tau2}|^2$ solar neutrinos $\Rightarrow$ Solar neutrinos potentially sensitive

$|U_{e1}|^2 \, |U_{e2}|^2$ KamLAND

$|U_{\mu3}|^2 \left(1 - |U_{\mu3}|^2\right)$ atmospheric/accelerator

$|U_{e3}|^2 \left(1 - |U_{e3}|^2\right)$ short baseline reactors

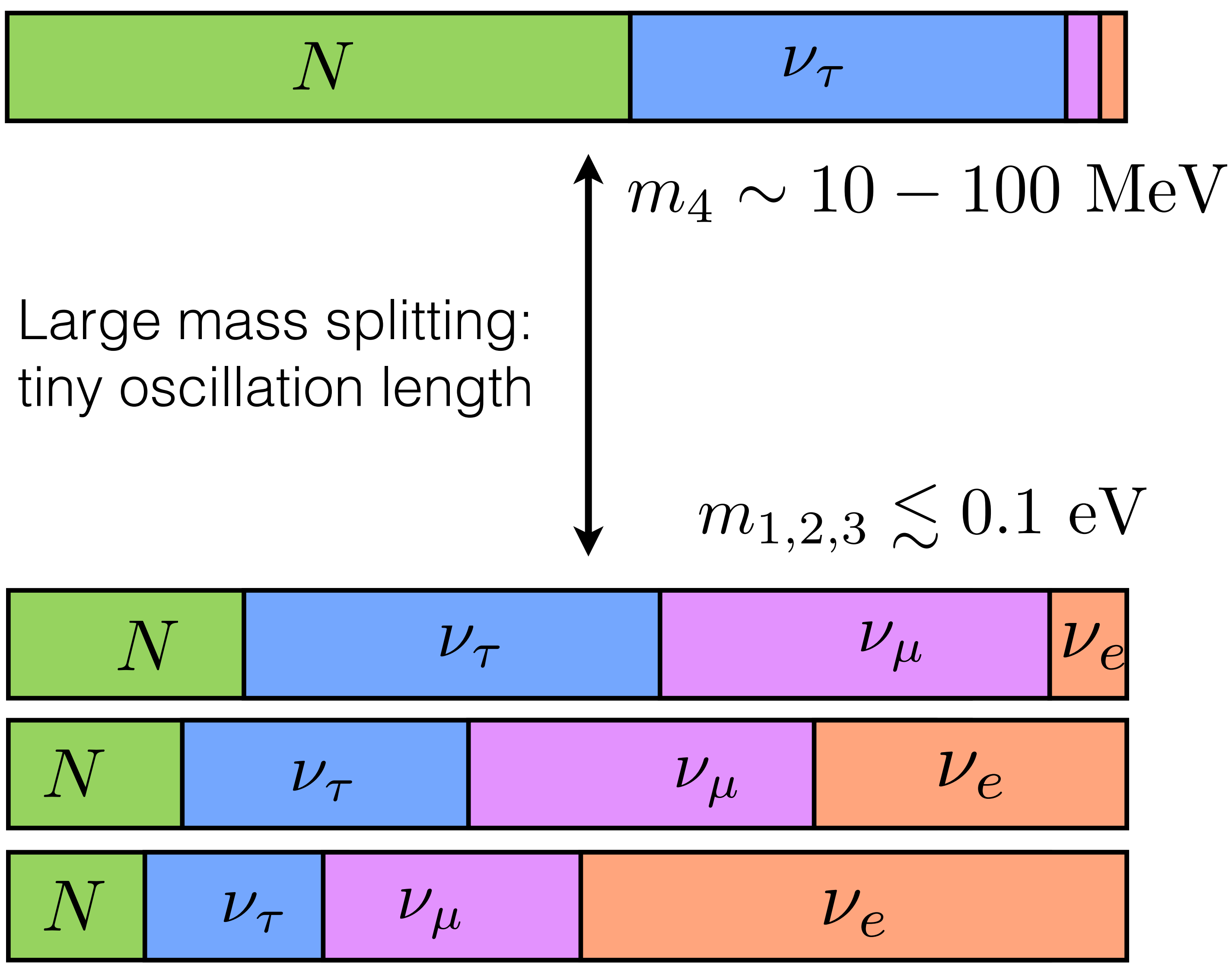
$|U_{e3}|^2 \, |U_{\mu3}|^2$ long baseline accelerator

Uncertainty on flux (^{8}B)~15%

$\sin\theta_\tau < 0.6$

Neutrino Oscillations

Assume mixing is dominantly with τ, just 1 more mixing angle in addition to the usual 3, and just 1 more (large) mass splitting



Light states admixtures of
$\nu_e,\ \nu_\mu,\ \nu_{\tau N} = c_\theta \nu_\tau + s_\theta N$
with usual solar/atmos. splitting

$$\Delta m^2_\odot \simeq 7.5 \times 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m^2_{\mathrm{atm}} \simeq 2.5 \times 10^{-3}\ \mathrm{eV}^2$$

$\theta_{12},\ \theta_{13},\ \theta_{23}$
not strongly affected by θ_τ

Atmospheric Neutrino Oscillations

$\nu_\mu,\ \nu_{\tau N}$ Hamiltonian:

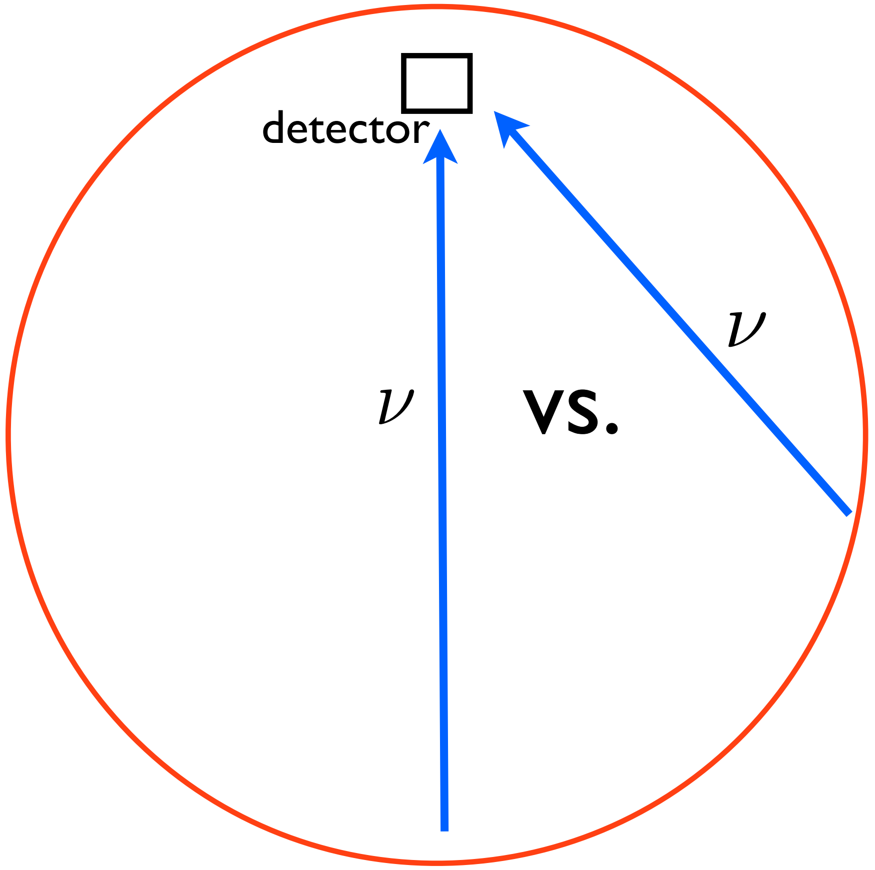
$$H = \left(\frac{\Delta m^2}{4E}\right)\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} + \begin{pmatrix} V_\mu & 0 \\ 0 & V_{\tau N} \end{pmatrix}$$

$$V_\mu = -\frac{G_F}{\sqrt{2}} n_n \sim \frac{1}{4000\ \text{km}}$$

$$V_{\tau N} = -\frac{G_F}{\sqrt{2}} n_n \cos\theta_\tau$$

[Non-standard int. $\epsilon_{\tau\tau} = \frac{1}{6}\left(\frac{V_{\tau N}}{V_{\text{nc}}} - 1\right) = \frac{\sin^2\theta_\tau}{6}$]

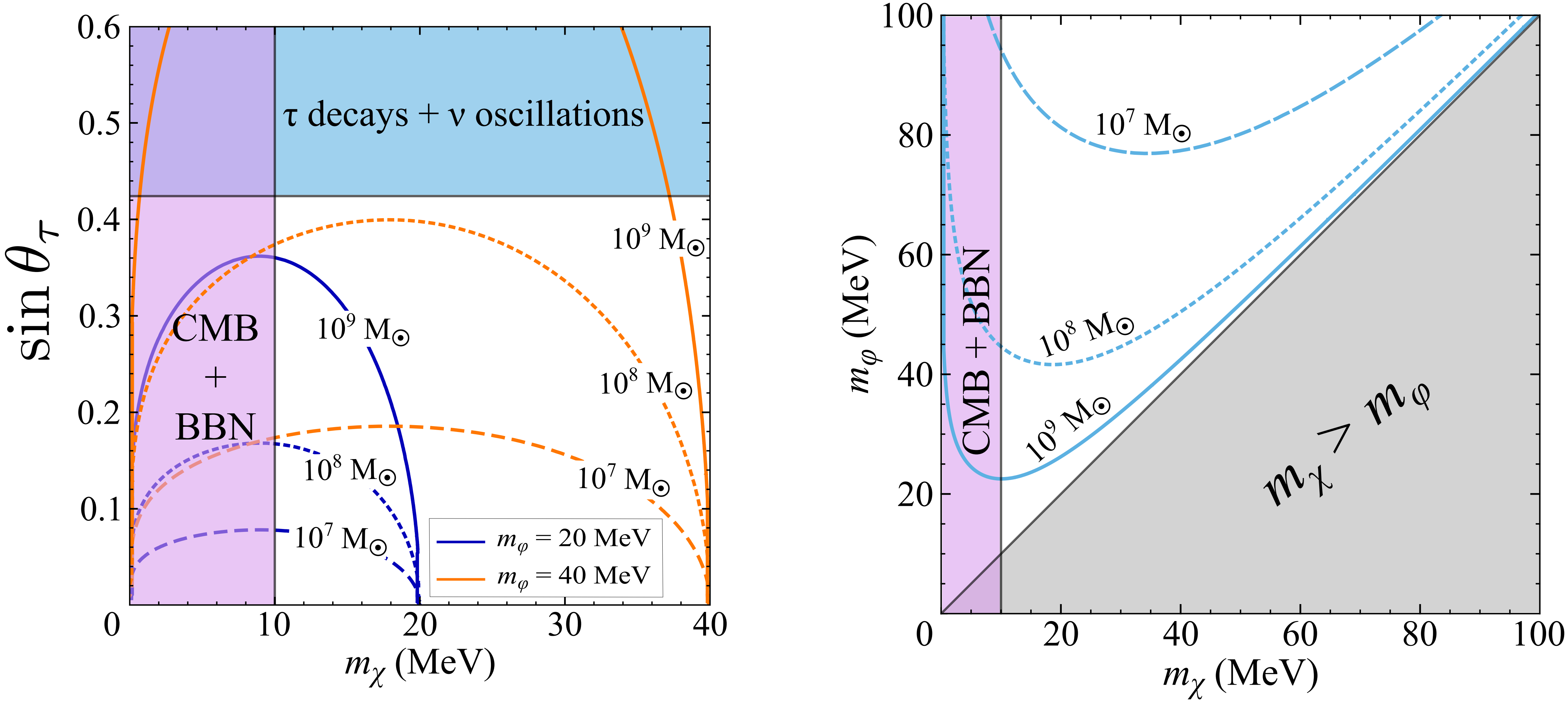
Oscillation pattern depends on amount of matter traversed



Super-K, arXiv:1410.2008

$\sin\theta_\tau < 0.42$ (stat. limited!)

Given these constraints, what M_{cut} can we achieve?

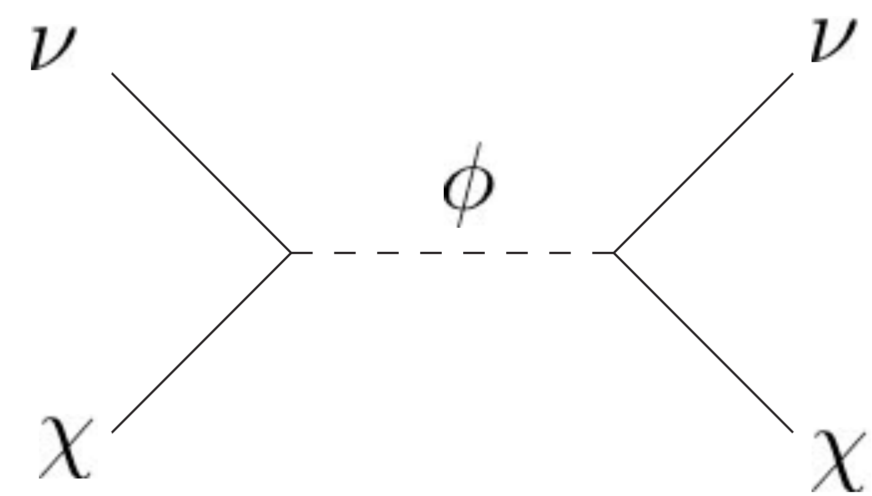


Find interesting values for 10-100 MeV masses

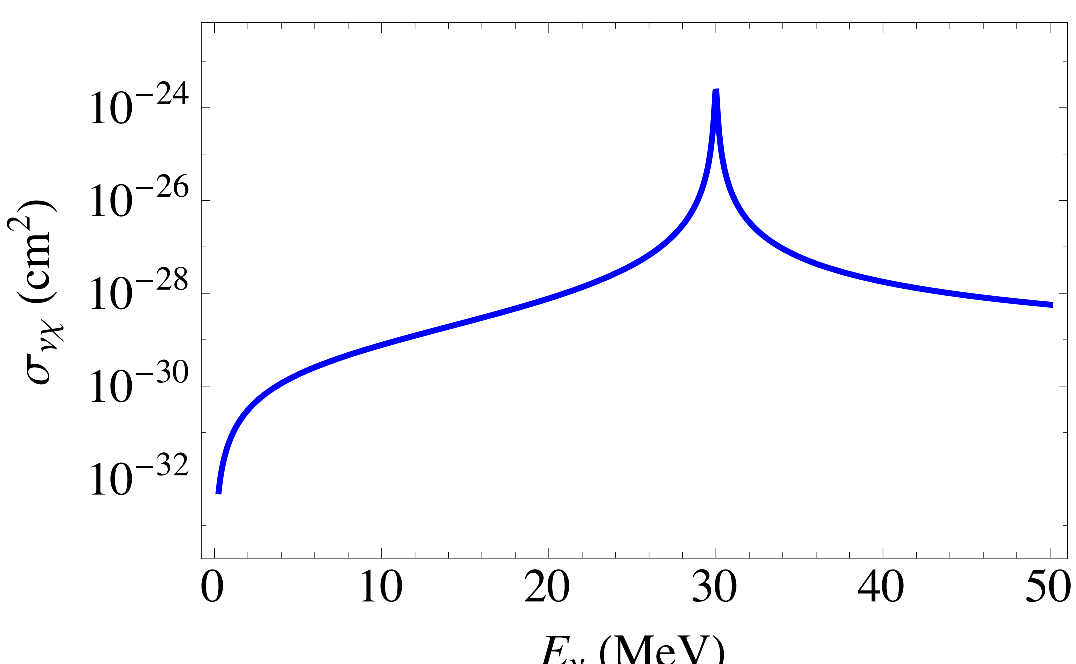
Other implications?

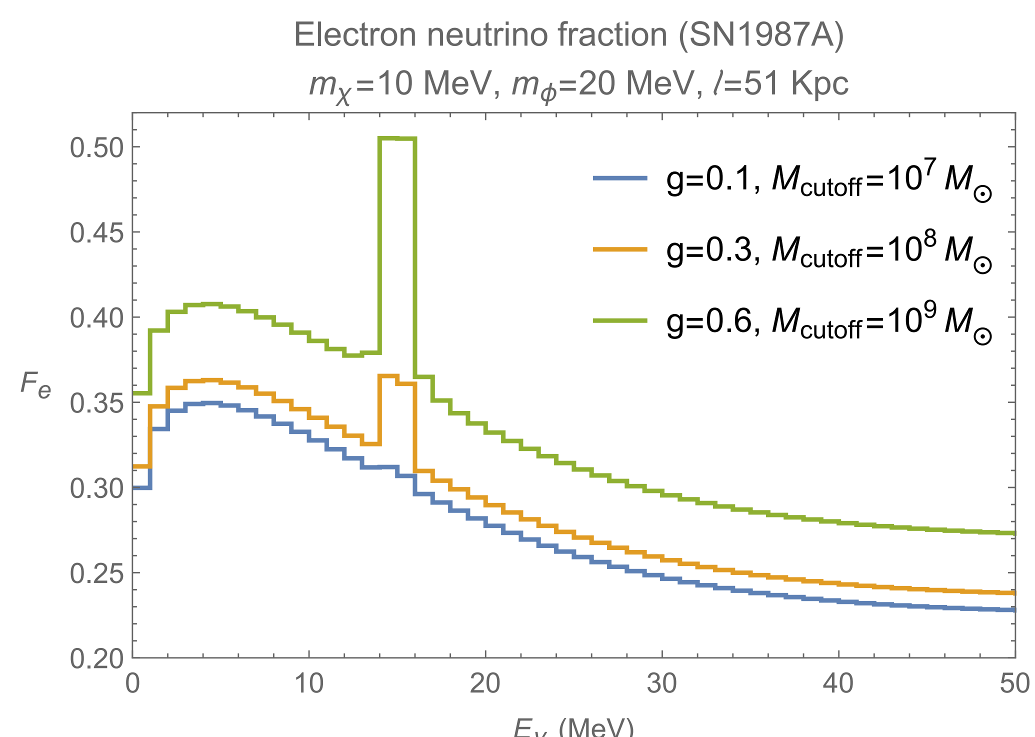
Neutrinos from Supernovae

MeV energy neutrinos from SN scatter on DM



Resonance at $E_\nu = \dfrac{m_\phi^2 - m_\chi^2}{2m_\chi}$ can be in the right range





$\mathrm{Flux}_i \propto e^{-\Gamma_i d}$ $\quad \Gamma = \sigma_{\nu\chi} \times \dfrac{1}{d} \displaystyle\int dx\, n_\chi$

$$\frac{1}{\Gamma_1} \simeq \frac{6}{\Gamma}, \quad \frac{1}{\Gamma_2} \simeq \frac{3}{\Gamma}, \quad \frac{1}{\Gamma_3} \simeq \frac{2}{\Gamma}$$

(Further work in progress w/ Bertoni, Nelson & Reddy)

Supernovae Limits

Neutrinos produced in SN at T~30 MeV

Initial neutronization burst of ν_e followed by cooling

DM light enough to be produced but doesn't contribute to cooling, thermal dist. with neutrinos to large radii

Neutrinos free stream when density is low, T~5 MeV: DM production suppressed, similar to strong ν self-interactions

Fayet, Hooper, & Sigl, hep-ph/0602169 find $m_\chi > 10\ \mathrm{MeV}$

Mangano et al., hep-ph/0606190 & Boehm et al., 1303.6270: $\sigma_{\hat{\nu}_i \chi} \lesssim 10^{-25}\ \mathrm{cm}^2 \left(\frac{m_\chi}{\mathrm{MeV}}\right)$

(Further work in progress w/ Bertoni, Nelson & Reddy)

Supernovae Limits

Large fraction of DM gravitationally bound: v_{esc} ~0.5 c

Is location (temperature) of ν-sphere changed?

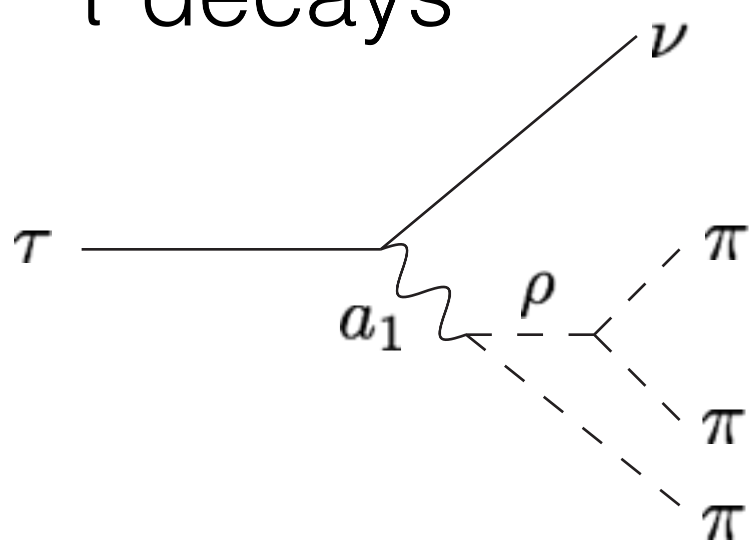
What are effects of flavor?

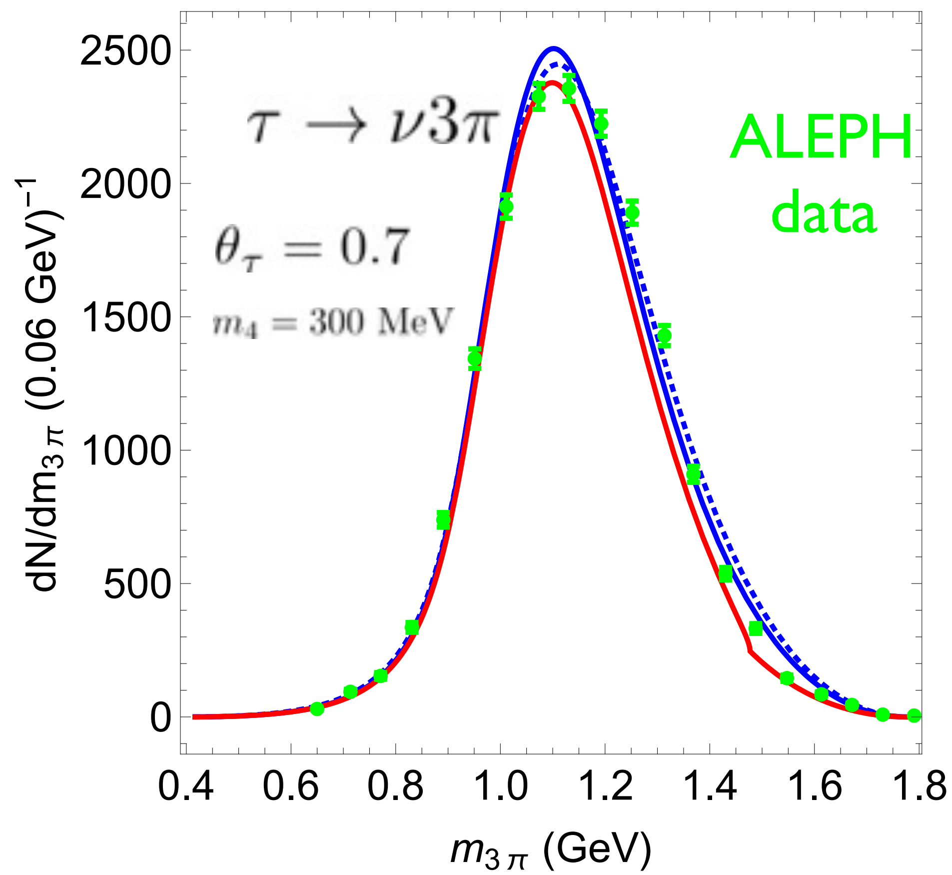
Could ν “dwell” time be increased?

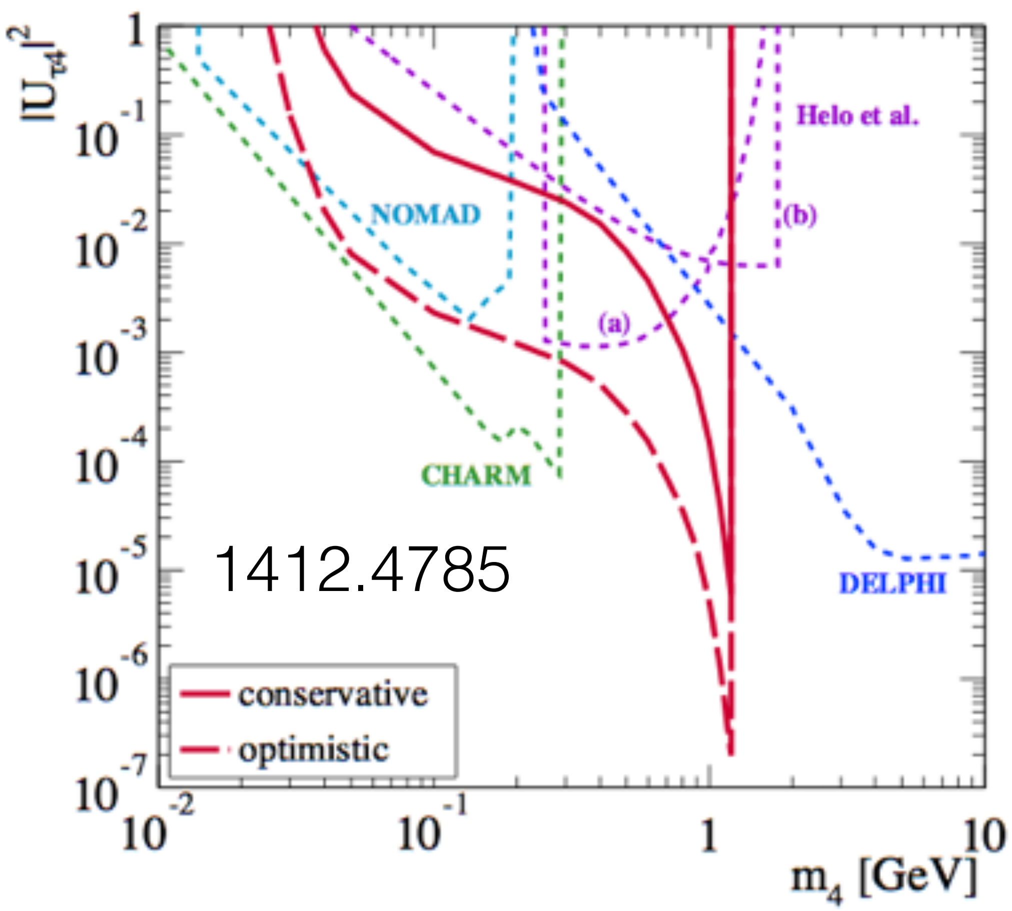
Very complicated…

Future tests

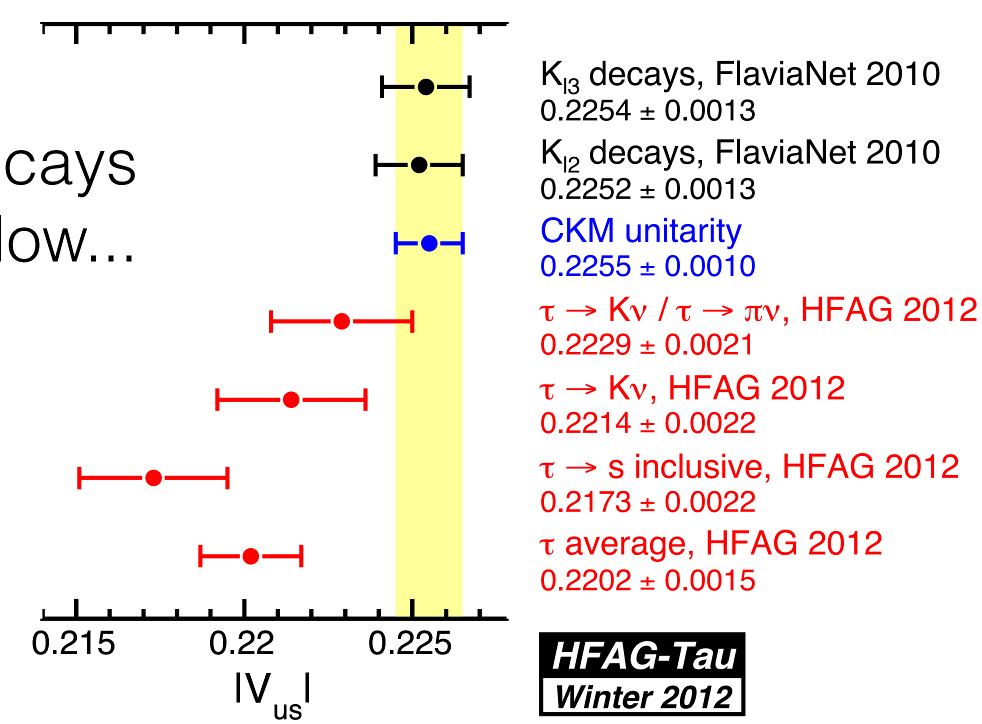
τ decays





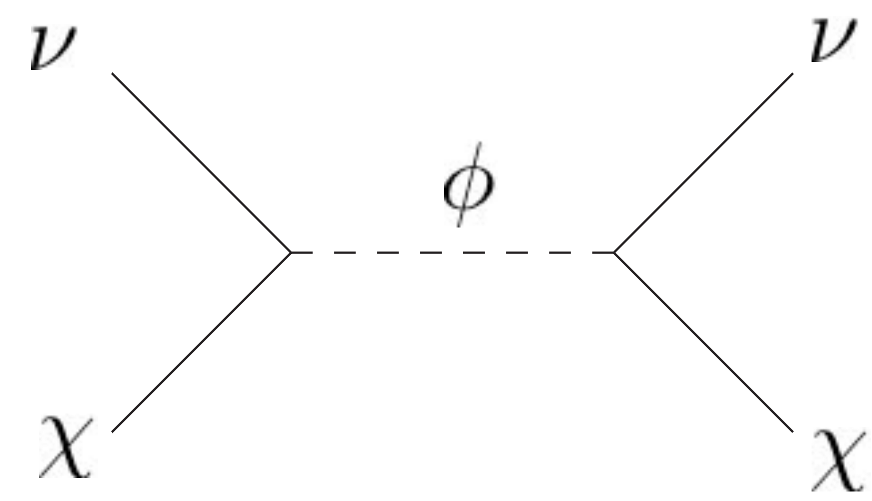


τ→K decays
slightly low...

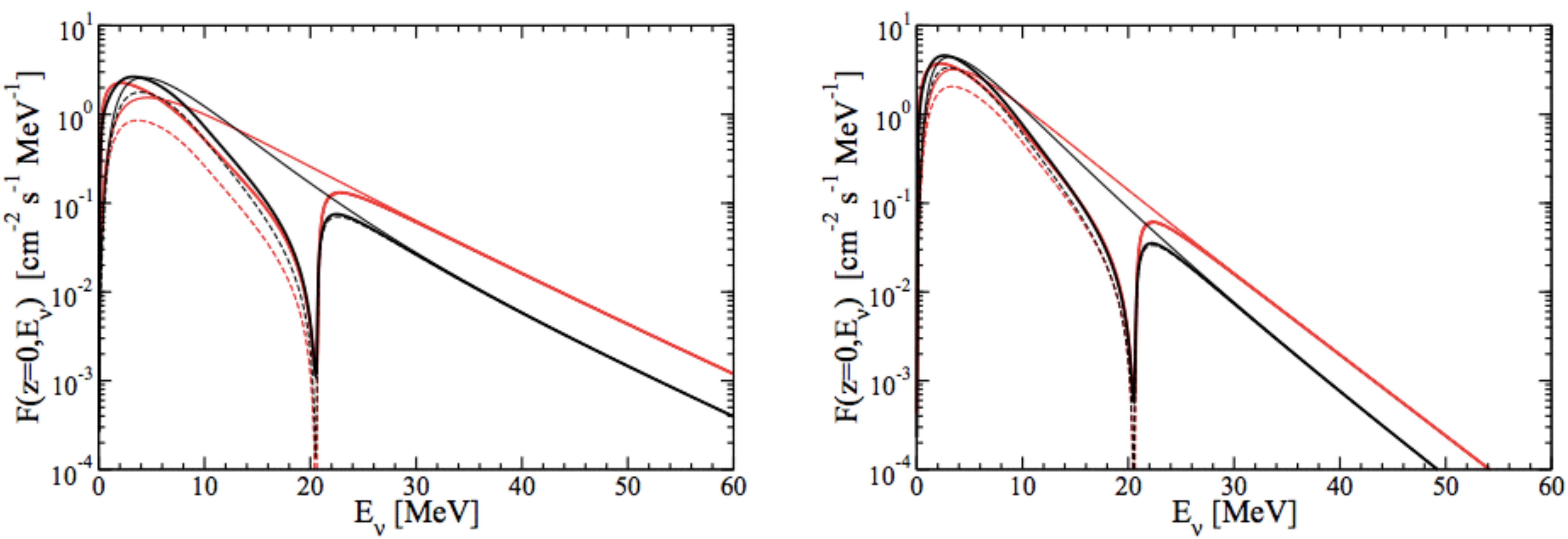


DSNB

Same process as for nearby SN



Farzan & Palomares-Ruiz 1401.7019



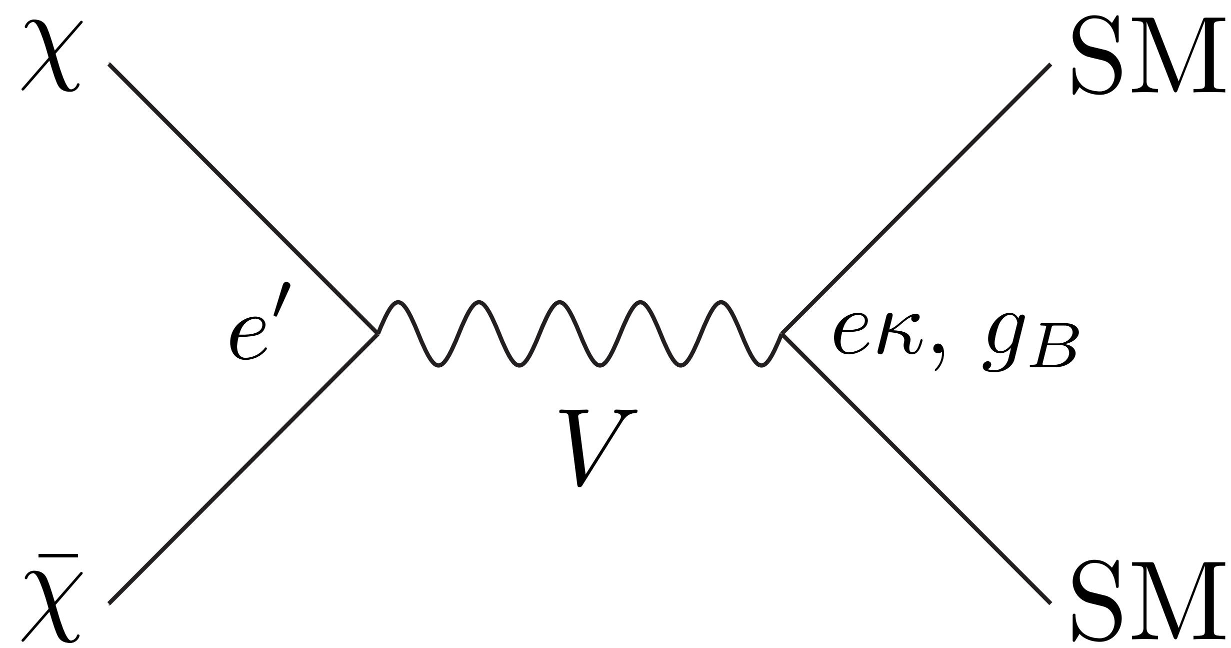
Potentially visible at Hyper-K

Another DM-neutrino (experiment) connection

Batell, deNiverville, DM, Pospelov, Ritz

A simple light DM model

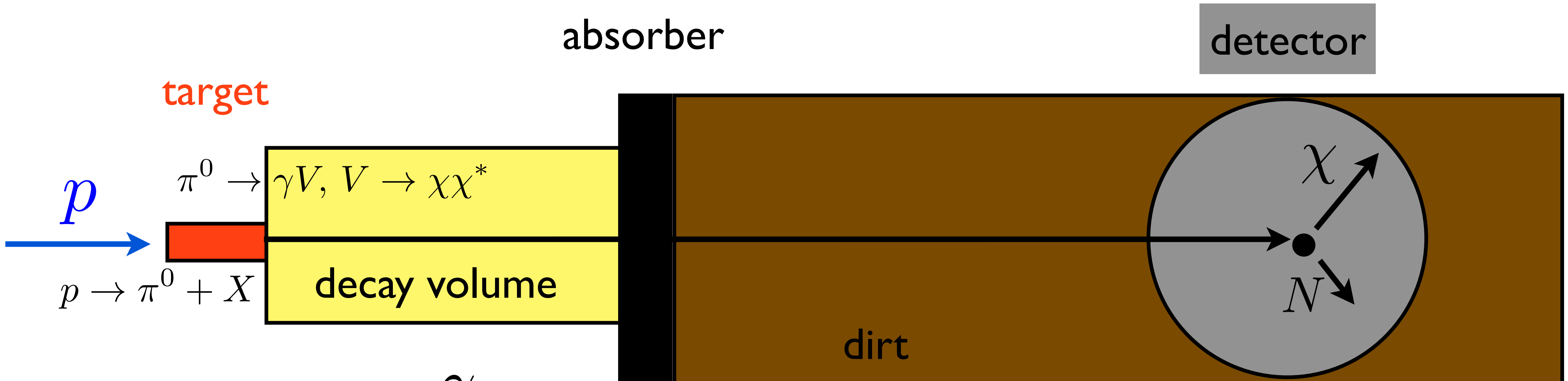
$$\mathcal{L} \supset \frac{\epsilon}{2} V^{\mu\nu} F_{\mu\nu}$$

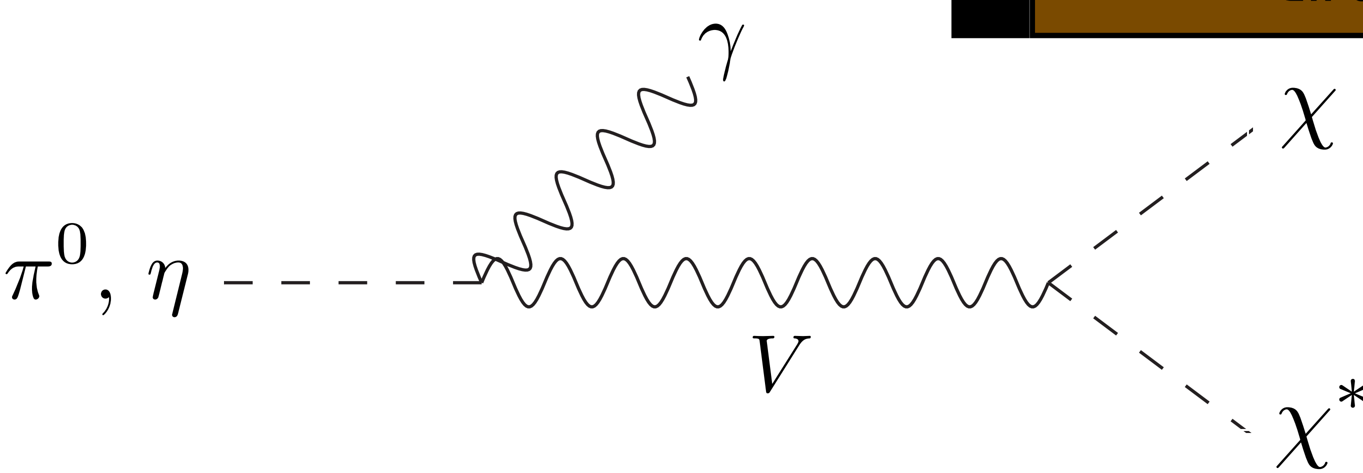


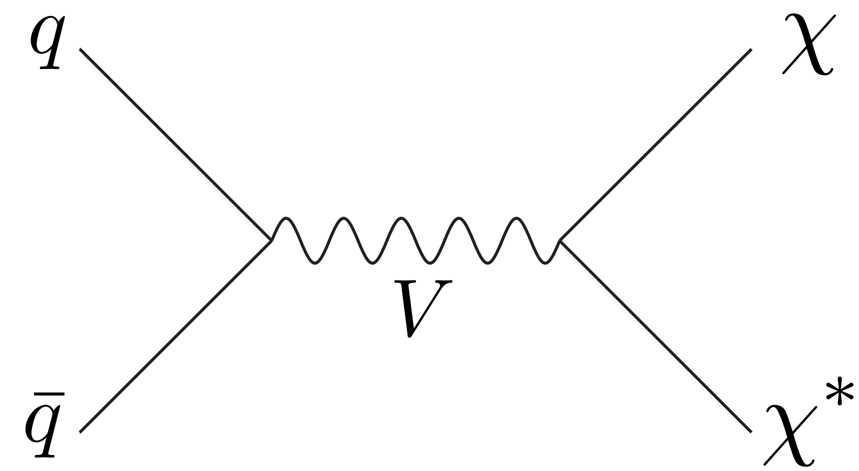
Light mediator allows Lee-Weinberg
bound to be avoided

See also Dobrescu & Frugiuele 1410.1566; Coloma, Dobrescu, Frugiuele, & Harnik 1512.03852

DM Production at Neutrino Expts.

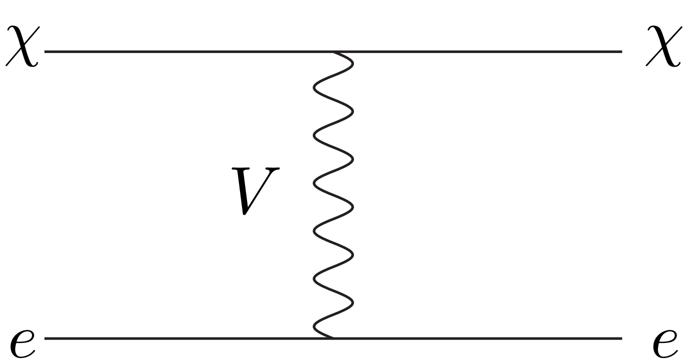




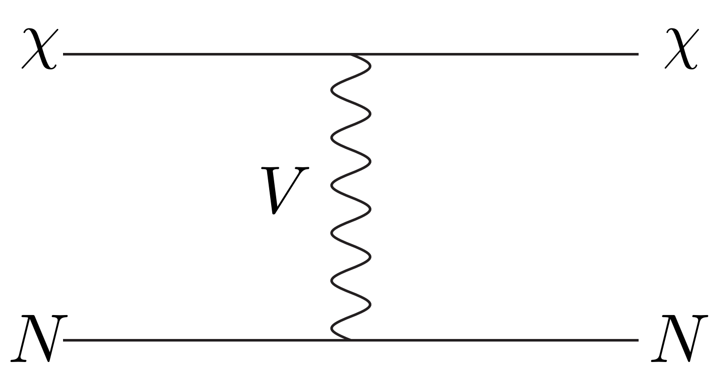


In the detector:

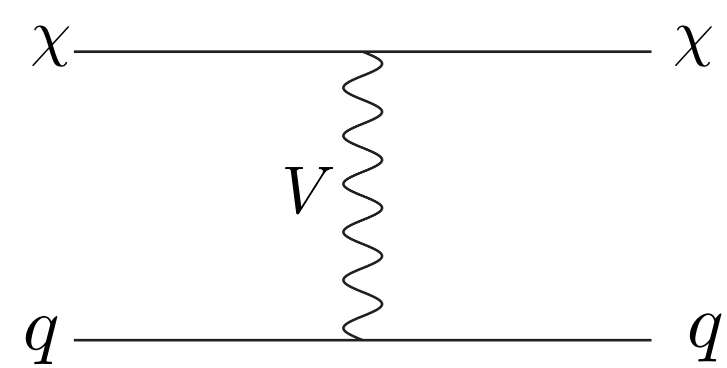
Elastic scattering on electrons



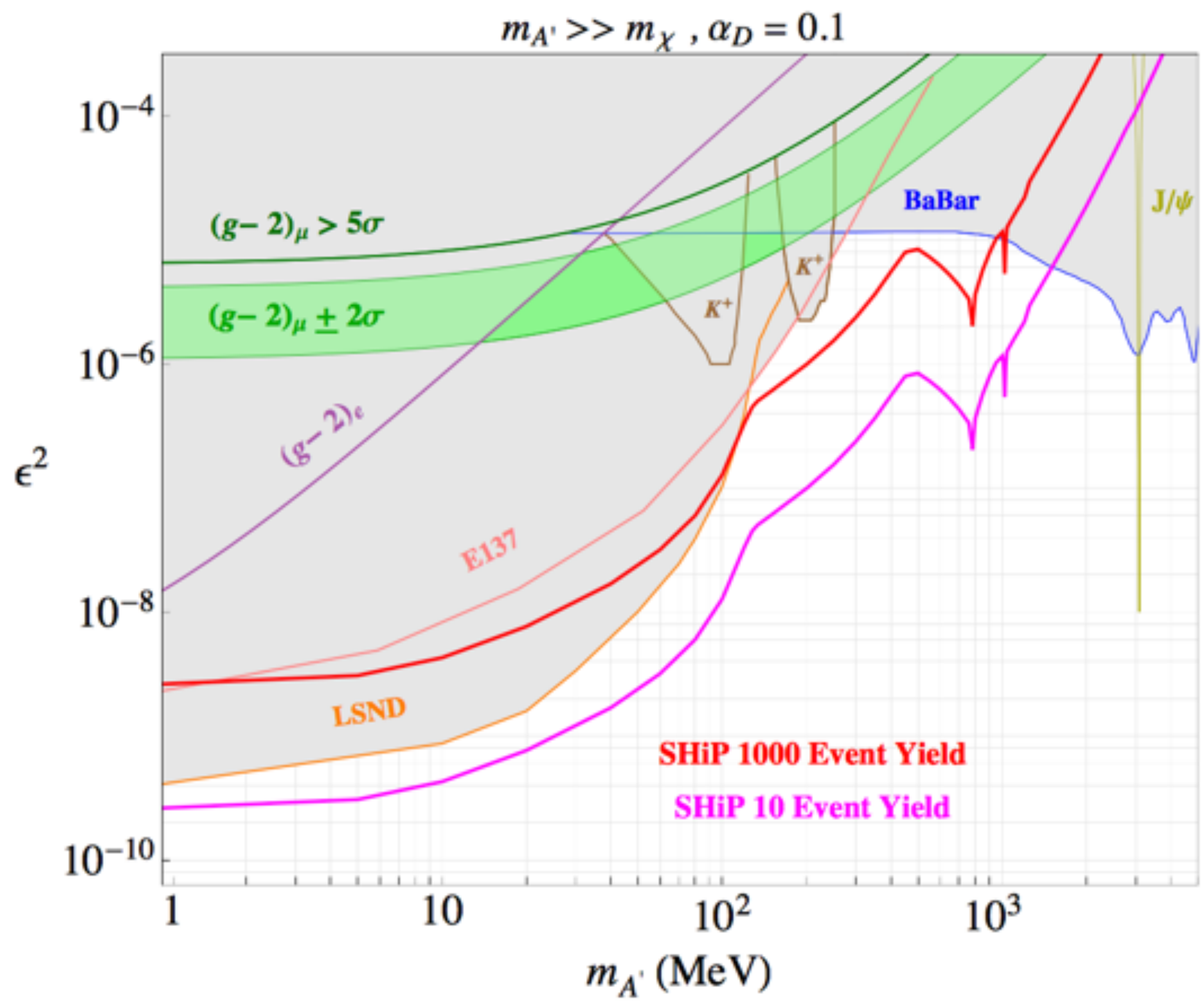
Elastic scattering on nucleons



Deep inelastic scattering



Interesting reach at future neutrino experiments



FERMILAB-PROPOSAL-1032 arXiv:1211.2258

Low Mass WIMP Searches with a Neutrino Experiment: A Proposal for Further MiniBooNE Running

Presented to the FNAL PAC Oct 15, 2012

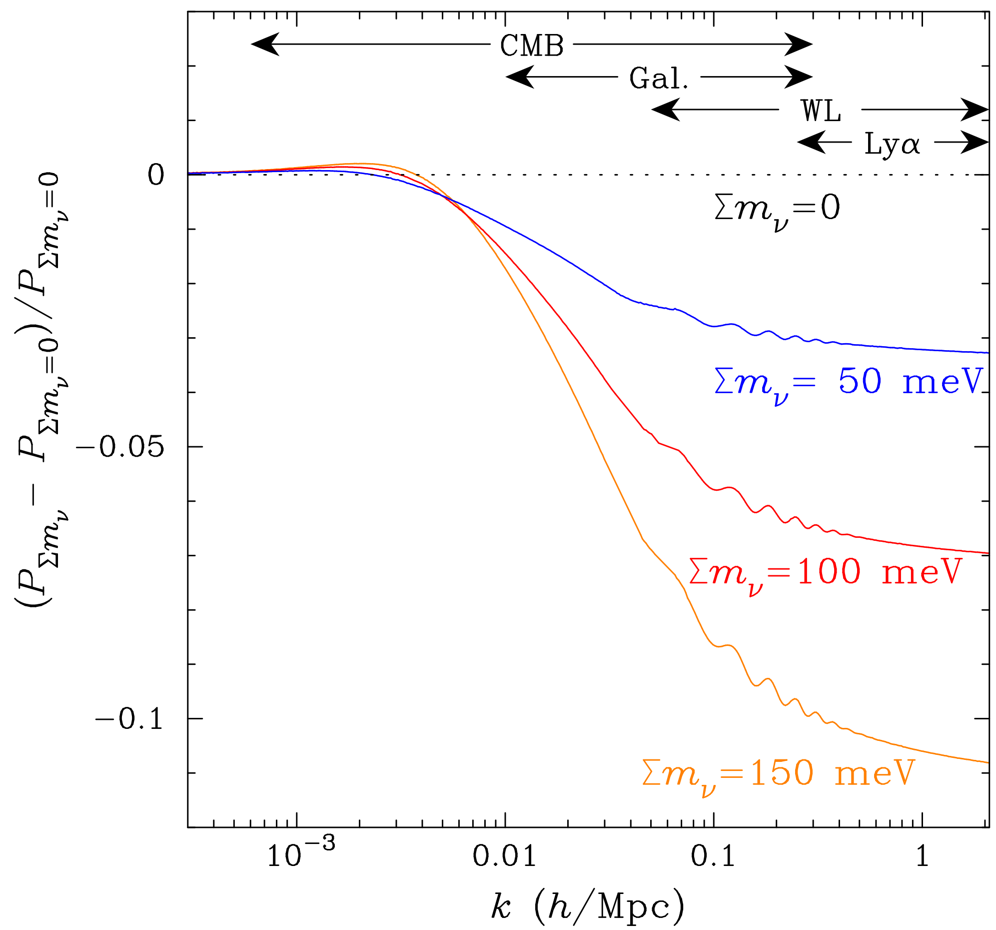
The MiniBooNE Collaboration
&
The Theory Collaboration

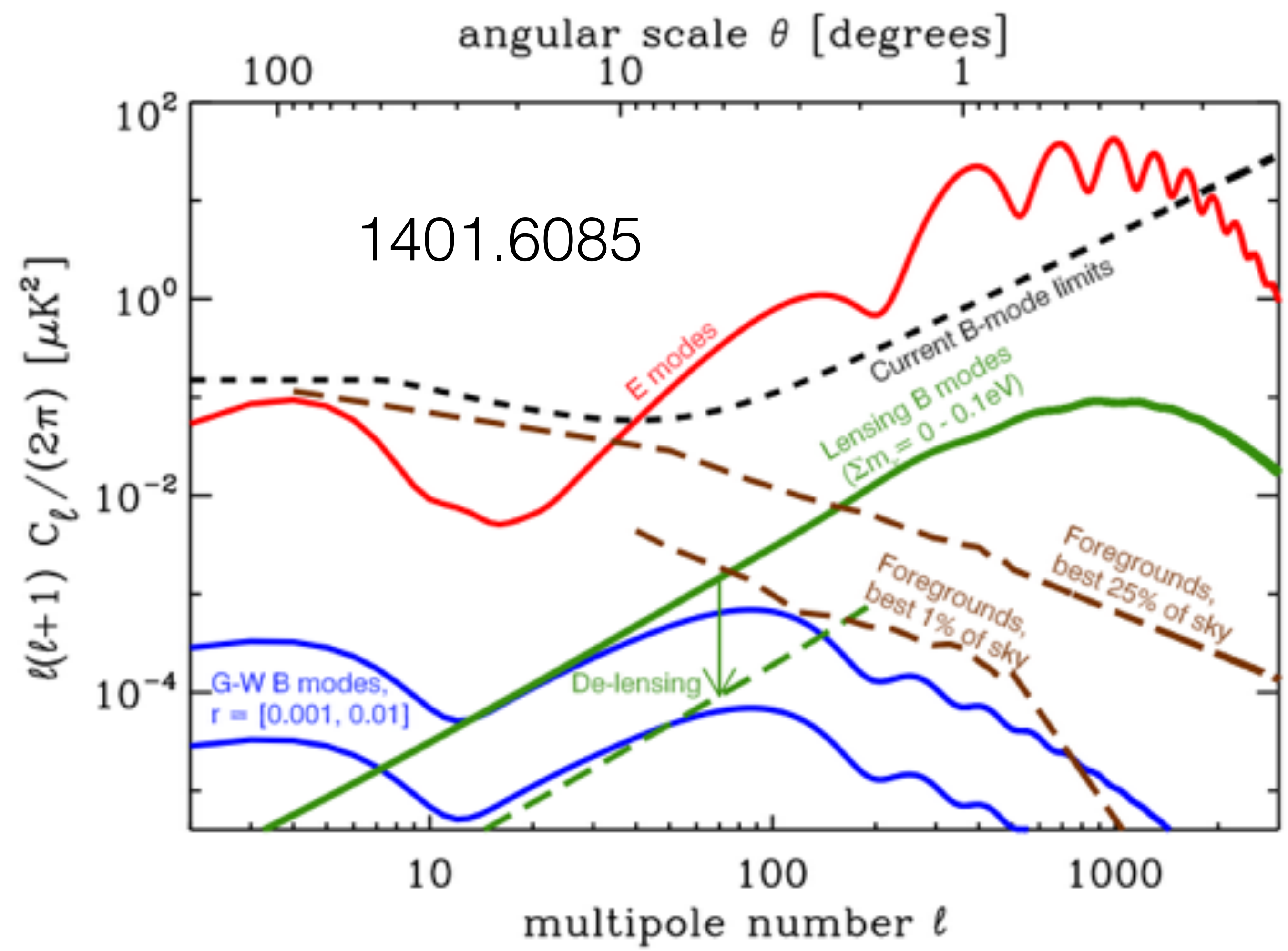
B. Batell
University of Chicago, Chicago, IL, 60637

P. deNiverville , D. McKeen, M. Pospelov, & A. Ritz
University of Victoria, Victoria, BC, V8P 5C2

Approved! Data taken, being analyzed…

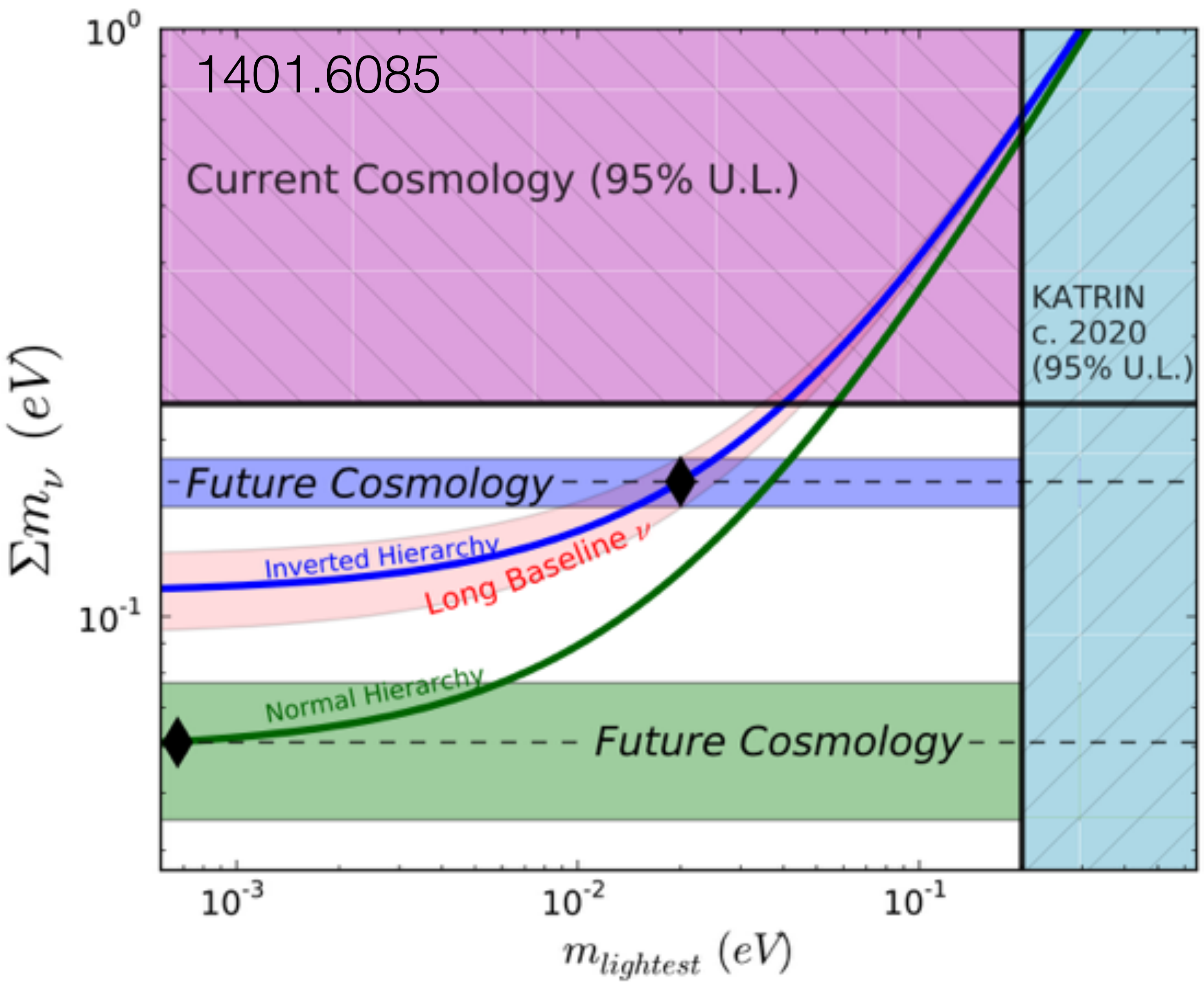
Neutrino mass vs. cosmology





Neutrinos affect structure formation, probed by galaxy surveys, lensing (CMB B-modes)

Future limits from cosmology on sum of neutrino masses will be very constraining



But these assume standard cosmology

⇓

Neutrino mass measurements/hints of massive sterile test this assumption!

Mass of neutrinos could be changing

[Fardon, Nelson, Weiner; Ghalsasi, DM, Nelson in prep.]

Story could be affected by neutrino interactions

[Dasgupta & Kopp; Fan & Langacker, …]

Wrap up

Neutrinos interacting with DM could explain puzzles

Low scales indicated, sensible models enable connections to neutrino physics

Neutrino expts. allow for opportunities to look for DM

Measuring neutrino masses here can *test* cosmological models